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SOME METALLOGRAPHIC RESULTS FOR BRUSH BRISTLES AND BRUSH SEGMENTS OF A SHROUD RING BRUSH SEAL TESTED IN A T-700 ENGINE

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SUMMARY

Post-test investigation of a T–700 engine brush seal found regions void of bristles ("yanked out"), regions of bent-over bristles near the inlet, some "snapped" bristles near the fence, and a more uniform "smeared" bristle interface between the first and last axial rows of bristles. Several bristles and four brush segments were cut from the brush seal, wax mounted, polished, and analyzed. Metallographic analysis of the bristle near the rub tip showed tungsten-rich phases uniformly distributed throughout the bristle, no apparent change within 1 μm of the interface, and possibly a small amount of titanium, which would represent a transfer from the rotor. Analysis of the bristle wear face showed nonuniform tungsten, which is indicative of material resolidification. The cut end contained oxides and internal fractures; the worn end was covered with oxide scale. Material losses due to wear and elastoplastic deformation within the shear zone and third-body lubrication effects in the contact zone are discussed.

INTRODUCTION

The preliminary results of T–700 engine brush seal testing have been reported in reference 1, and the post-test metallographic work on that same seal is described herein. The split-ring brush seal was fabricated, installed between two labyrinth-honeycomb shroud seals, and tested in the fourth-stage turbine of a T–700 engine (fig. 1, ref. 1).

Brush Seal Geometry

The brush seal was made up of 0.0028-in. (0.071-mm) diameter Haynes 25 bristles angled 43° to 50° to the interface with about 2500 per inch of circumference (98.4 per millimeter of circumference) (fig. 2(a)). The backing washer was angled 19° to match the slope of the turbine shroud (fig. 2(b)). The design clearance was −0.02 in. (−0.51 mm) but could range to −0.05 in. (−1.27 mm) diametral (the uncertainty reflecting that of the engine geometry) with an outside diameter of 13.146 in. (333.9 mm) and an inside diameter of 12.690 in. (322.3 mm).

Operating Conditions and Interface Geometry

The annealed Haynes 25 bristles rubbed directly against the nonconditioned, irregular René 80 turbine blade shroud surface. Turbine speeds were 10 000 and 20 000 rpm, and average fourth-stage turbine shroud temperatures were 850 and 1050 °F (455 and 566 °C), respectively. The turbine inlet temperatures were about 250 deg F (139 deg C) higher.

The turbine assembly has 50 shrouded blades with irregularities (radial, to 0.009 in. (0.023 mm); circumferential, to 0.003 in. (0.076 mm); and axial, to 0.002 in. (0.0051 mm)) representing protrusions into the brush and the spaces between the blade pairs. It is not known how many cycles were required to "free the bristles," but at 10 000 rpm and with 50 irregular asperities impacting each bristle (4000 impacts/s at a surface speed of 550 ft/s (168 m/s)), it is assumed that brush break-in was rapid.

A total of 21 hr of cyclic and steady-state data were taken with surface speeds to 1100 ft/s (335 m/s) and shroud temperatures to 1150 °F (620 °C). Wear appeared to be rapid initially, with a orange flash of hot brush fragments during the first engine startup, but decreased to none in less than 10 hr of operation.

Tribological Pairing

Derby and England (ref. 2) reported minimal brush and coating wear using an Alloy A bristle with Triboglide coating. Alloy A (a solid-solution-strengthened, nickel-chromium-aluminum-based superalloy) is being used in gas turbine hot spots and develops a tenacious chromia (Cr_2O_3) and alumina (Al_2O_3), yttria-modified oxide layer. Triboglide is a chromium carbide (CrC) containing a total of 12 wt % barium and calcium fluoride solid lubricants. Triboglide is based on the work of Harold Sliney at NASA Lewis Research Center but has no silver additive. The tests were performed with 1200 °F (650 °C) air.

Atkinson and Bristol (ref. 3) reported less wear for a cobalt-based alloy rubbing against CrC at room temperature than for a nickel-based alloy but nearly equivalent wear for either alloy at 480 °C (900 °F). However, the cobalt combination proved to leak less under dynamic conditions and wear less at room temperature. The tests were conducted to simulate a CT7–9 compressor discharge seal. The brush was 5.08 in. (129 mm) in diameter and of standard Cross Mfg. construction.

Hendricks et al. (ref. 1) reported the results of a T–700 engine test. Details of the bristles (fig. 3(a)) show an ingrained wear pattern that is characteristic of a high spot in the rotor which cuts a shallow groove as the rotor wears the brush. The rotor also ran eccentric with respect to the seal, and the blind installation made it difficult to assess intermediate states of wear or the health of the brush and the turbine shroud/brush interface.

Metallographic results illustrate some material migration along the bristle and material transfer both from and to the rotor surface (fig. 3(b)). Material smears seem to be in line with the softer brush material rubbing a harder material; the sacrificial bristles appear to be oxidized, pitted, and rubbed by line-to-line contact. It is not clear how the interface irregularities affected these results, but it is clear that materials were transferred and that they probably melted upon initial rub-in due to the high interface temperature.

Before the brush seal for the T–700 engine test was manufactured and installed (ref. 1), a 40-tooth rotor was used to gather debris, wear, and cycle information in an attempt to simulate the harsh geometric environment of the engine test. The bristles did wear significantly, produced only powder-like debris, and had no failures in over 10^9 flexure cycles of operation (ref. 4).

Tribological pairing is important and references 1 to 4 provide an initial look at the problem. It is apparent that the compositions of both the coating and the bristles need to be characterized with respect to the working fluid, the operating conditions, and the component life requirements. Also, the importance of surface conditions must be emphasized, noting that wear decreases after operation both because the brush rubs a smoother surface and because bristle wear decreases line loading.

Herein, we provide further details of the results of the brush seal engine testing described in reference 1.

ANALYSIS AND DISCUSSION

Several bristles (wires) and four sections of the brush seal tested in a T–700 engine (ref. 1) were cut, wax mounted, polished, and analyzed. The bristles and sections were mounted in a low-melting-point wax, rough lapped with 3-μm diamond grit, polished with 1-μm diamond grit, and coated with palladium for light optic and scanning electron microscope viewing.

Bristles Cut From Brush Seal

Bristle tip irregularities caused by the rub interface (fig. 4) indicate some form of material transfer and material smearing. However, metallographic analysis of the bristle near the rub tip showed tungsten-rich phases distributed throughout with no apparent change within 1 to 2 μm of the interface. Figure 5 shows a bristle wear surface and little or no evidence of a redistribution of tungsten indicative of resolidification. From the Blok problem (ref. 5) the temperature was sufficient to melt the bristles, but the materials may fail in shear before melting (like pulling a taffy), form oxides and pits, transfer to the interface or form layers less than 1 μm thick, wear away, or all of the preceding.

Figure 6 illustrates a wear surface, although because the tip is embedded and angled, the photograph does not always provide a true representation of the surface. From 2 μm to several millimeters from the interface, there appears to be no change in tungsten composition. Green dots are near the edge (micrometer range) and red is away from the edge (millimeter range), showing little or no change in tungsten distribution, but the surface appears to be coated (oxides are discussed later).

The wear marks and the pocked bristle tip (fig. 6) were examined at higher magnification (fig. 7). Backscatter images show heavy atomic particles as bright spots and lighter weight elements as dark spots. Secondary electron images show tungsten but at a lesser brightness. Backscatter tends to change with geometry and higher magnification and wax mounting effects must be differentiated, but the interface wear marks show clearly. The bright spots are tungsten rich as noted by the element spectra, and the spot on figure 7 is a beam concentration spot obtained by energy-dispersive spectroscopy of a bright tungsten-rich region.

At resolutions of 10 000X, there is no apparent change in tungsten at the bristle edge but there is possibly a small amount of titanium, which would represent a transfer from the rotor (rotor scrappings are discussed later). Again little evidence of resolidification but more evidence of oxide scale is noted.

Oxide scale formation on the bristle (fig. 8) was most likely chromium oxide, which can form, rub (flake), and reform thus providing a third-body lubrication effect. Such surfaces are also noted in figures 6 and 7. A scale formation noted as a dark region (lower atomic number) showed decreases in tungsten and cobalt with significant increases in oxygen. A more detailed analysis was conducted on bristles also cut from the post-test brush seal. Micrographs of a cut end and a rubbed (worn) end are shown in figure 9 with the associated element spectra in figures 10 and 11, respectively. The cut end contained oxides and internal fractures (figs. 10(a) and (b)). The worn end was covered with scale that at 5000X appears to be oxide scale (figs. 11(a) and (b)). The oxygen level from the cut to worn ends increased from 5.7 to 12.7 percent; the cobalt level decreased from 32.5 to 22.0 percent; and the chromium level dropped from 24.4 to 22.3 percent.

The bristle element spectra are dominated by cobalt, chromium, and tungsten lines representative of a cobalt-based alloy such as Haynes 25 (table I). Most spectra show oxide scale and little material transfer from the René 80 rotor (table I) to the bristles. However, increases in nickel and molybdenum (fig. 12) illustrate that some material transfer from the rotor to the bristle tips did occur. Nevertheless, scrapings from the René 80 rotor-bristle wear track (fig. 13; see also fig. 3(b)) were rich in cobalt, which is characteristic of Haynes 25 transfer to the rotor. Therefore, the sacrificial elements were the Haynes 25 bristles, as designed.

With significant material transfer to the rotor and oxide scale formation over the bristle surface, an examination of a bristle tip (fig. 14) showed wear traces, pitting, and material transfer. Figure 15 illustrates that although the base material appears as Haynes 25, the distribution of tungsten differs as noted in the element spectra. Therefore, some form of resolidification must have occurred right at the bristle–rub runner interface.

Note that these tests were conducted in the fourth stage of a shrouded turbine disk where the fluids to be sealed were combustion gases, with cooling air to 1200 °F (650 °C). The principal elements of such gases are oxygen, steam, carbon dioxide, and nitrogen. In the tests conducted at GE (ref. 3) and at EG&G (ref. 2) the working fluid was probably air (0.8 N_2 and 0.2 O_2 approx.) at temperatures to 1200 °F (650 °C) (equivalent to our shroud temperatures) at EG&G and to 480 °C (895 °F) at GE. Both are above the transition temperature for cobalt (ref. 2). Also, note that the T–700 engine was probably fuel rich on startup and lean on shutdown so that oxide scaling could occur by engine air cooling of the heated bristles and by steam corrosion. Also, the GE tests were for 100 hr, the EG&G tests were for 1.5 hr, and the T–700 tests were for 30 hr.

Some additional micrographs illustrated carbon spots on the bristle surfaces (fig. 16). Bristle tips and irregular bristles found in the exhaust duct of the T–700 engine are shown in figures 17 and 18. Oxide scaling is noted but also apparent is a form of resolidification. The events associated with bristle loss at engine startup are discussed in reference 1. In this regard the reader is reminded that the brush was installed and disassembled "blind" (ref. 1).

Brush Segments Cut From Brush Seal

Sections were taken along the bristles of four segments of the T–700 brush. None of these showed evidence of melting at or near the interface. All showed material distortion due to both shearing and abrasive wear, with suspected material softening at elevated temperatures as a major contributor. All exhibited oxide formation, which presumably would scale off at some later time or embrittle the entire wire causing fracture. There was some evidence of melting and debris near the pinch washer interface, which after T–700 testing was close to the bristle–rub runner interface. A few bristles were sectioned along the length, but in general the bristle geometry did not conform to a uniform array. The reason was partially the construction method, partially the misalignment of the bristles and polishing plane used, and mostly the engine operations and the abusive nature of the segmented turbine blade rub interface.

Oxide formation at elevated temperatures and shear flow of materials appears to have caused the interface to smear, forming "mudflat" segmented structures (fig. 19) rather than the uniformly spaced elliptical footprints of the preinstallation grinding.

One segment evidenced some material transferred from the backing plate and rubbed into the brush. At this location the rotor did rub the backing plate, and the bristle stubble was nearly line to line with the backing plate. But the transfer could have resulted from electron beam discharge cutting of the seal.

Figure 20 illustrates brush segment 1, which was cut from the seal at the maximum bristle stubble location; see figure 3(a). A critical analysis was not done on this section, but a closeup of the fence surface is given as figure 20(a).

Some of the pitting in brush segment 2 (fig. 21) may be due to electric discharge cutting of the sections, with the bristles investigated too near that interface. The polishing plane and the bristle planes are not all aligned and bristle tips are shown along with some bristles in the polishing plane. It is evident that the last bristle row is bent under the fence, but not so evident is when it happened. Backscattering electron photographs show uniform distribution of tungsten spots, some oxide formation, and some local fracturing of the smeared bristle tip. Color element traces show tungsten-rich white spots, oxide formation and the bristle matrix. The chromium diminished as the oxide increased or was leached out of the matrix. A closeup of the fence surface is shown as figure 21(b).

Brush segment 3 (fig. 22) shows some evidence of melting and material debris from the backing plate or from the weld interface. The melt region is rich in redistributed tungsten, a factor that may have to be reevaluated as a manufacturing procedure. The color element traces show oxide formation between two bristles.

In brush segment 4 (fig. 23) the polishing plane and the bristle planes differ, yet oxides and smeared materials are apparent. The color element traces show the composition of the backing plate materials and the oxide that is formed on the bristle tip and around the bristle. Also observed is a bead that mimics the composition of the backing plate and may have come from the rubbed interface or the disintegration cutting of the ring.

Brush Seal Configuration

The post-test brush seal was examined by using a micro-video system. Several irregularities associated with installation were noted. One region was void of bristles (fig. 24(a)); perhaps they were yanked out. Adjacent bristles were all bent over (fig. 24(b)) on the leading edge but not in the core. One bristle of original length was kinked at the tip and appeared to be approximately 2.5 times as long as the remaining bristles (fig. 24(c)). A closer look revealed some "snapped" bristles in that region (fig. 24(d)), perhaps from forcing the brush into position or from catching bristles within the turbine blade gaps. The snapped bristles were very close to the pinch washer. Bristles near the pinch washer were broken and/or bent, but deeper into the brush bristle pack (N_x) the bristles were straight and worn (fig. 24(e)). The appearance of the first three rows N_x of the brush showed erratic rubbed wires, probably due to installation deformations. For $N_x > 3$ the appearance is more uniform for the next nine rows. Higher magnification of the interface shows "smearing" of the bristle tips (fig. 24(f)). Each bristle appeared to have some scale covering it (fig. 24(g)) as evidenced from wire highlights and differential coloring, like air-quenched steel.

Other effects of the rubbing interface are discussed in references 1 and 4.

CONCLUSIONS

Post-test evaluation of brush bristles and brush sections cut from the brush shroud seal run in the fourth-stage shrouded turbine disk of a T–700 engine provided the following information.

Cut Bristles

1. Bristles cut from the brush showed little or no evidence of tungsten redistribution, indicating that little or no resolidification had occurred over the bristle length.

2. Bristles exhibited surface oxidation, pitting, color differentials, and scaling over their lengths with significant oxidation at the rub interface. Bristle tips were irregular in shape.

3. Rotor scrapings showed material transfer from the Haynes 25 brush to the René 80 rotor. The brush was sacrificial, as designed.

4. The bristle tips showed irregular distribution of tungsten, which is indicative of resolidification in a very thin layer at the rubbing interface.

Cut Sections

5. Oxides formed on bristle surfaces, with significant material losses at the interface. Bristles became more brittle.

6. Material dislocation and bristle distortion were high at and near the interface. Wear was high owing to the extreme test conditions.

7. The uniform distribution of tungsten indicated that no melting had occurred at or near the interface. Material softening with attendant shear deformation is postulated as a material smearing mechanism; see also the fourth conclusion.

8. Post-test investigation revealed the "mudflat" appearance of the interface in contrast to the "polished," distinct elliptical bristle ends noted before the test.

Seal Configuration

9. "Blind" installation and forcing the brush onto segmented rotors can lead to distortion of the first few and last bristle rows and to local pullout.

10. Bristle tip smearing at the rub interface was commonplace, with mudflat cracking but with a uniform wear track.

11. Some formation of bristle debris at startup was noted.

12. The mechanical aspects of the brush survived the harsh test environment.

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2. Derby, J.; and England, R.: Tribopair Evaluations of Brush Seal Applications. AIAA Paper 92–3715, 1992.

3. Atkinson, E.; and Bristol, B.L.: Effects of Material Choices on Brush Seal Performance. Lubr. Eng., vol. 48, no. 9, Sept. 1992, pp. 740–746.

4. Hendricks, R.C.; Carlile, J.A.; and Liang, A.D.: Brush Seal Bristle Flexure and Hard Rub Characteristics. NASA TM–105864, 1992.

5. Carslaw, H.S.; and Jager, J.C., eds.: Condition of Heat in Solids. Clarendon Press, Oxford, Second ed., 1959, p. 269.

TABLE I.—COMPOSITION OF RENÉ 80 AND HAYNES 25

Composition, wt %	
René 80	Haynes 25
60 Ni[a]	50 Co[a]
14 Cr	20 Cr
4 W	15 W
9.5 Co	10 Ni
4 Mo	3 Fe
3 Al	1.5 Mn
5 Ti	0.1 C
0.17 C	
0.015 B	
0.03 Zr	

[a]Balance.

TABLE II.—SUGGESTED BRUSH SEAL SYSTEM TRIBOPAIRS

Bristle materials	Rub runner	Lubricated runner or bristle
SiC Al_2O_3 Haynes 25 L605 AMS5796 Haynes 188 AMS5801 Haynes 214 Haynes 230 MA 754 MA 956 In X750 Waspalloy Lubricating coatings	Inconel X750 Inconel 718 Al_2O_3: Union Carbide LA2 Metco 105NS, 105SF TiN Cr_2O_3 WC (Union Carbide) CrC (Union Carbide): LC-1-B LC-1-C Diamond Allison 250-C30 material CrCo MoC Wear Cote CF_x/EN YSZ Ion implantation combinations	Triboglide PS 212 Wear Cote YSZ + $BaTiO_2$

Operations goals	Material	Temperature, K (°F)	Surface velocity,[a] m/s (ft/s)
1	Metallic	4 to 1090 (−455 to 1100)	0 to 350 (0 to 1100)
2	Metallic/ceramic	4 to 1145 (−455 to 1600)	0 to 395 (0 to 1300)
3	Ceramic	4 to >1370 (−455 to >2000)	0 to 457 (0 to 1500)

[a]May be achieved with metallic configurations with line-to-line contact, but rubbing will sacrifice the interface with attendant leakages.

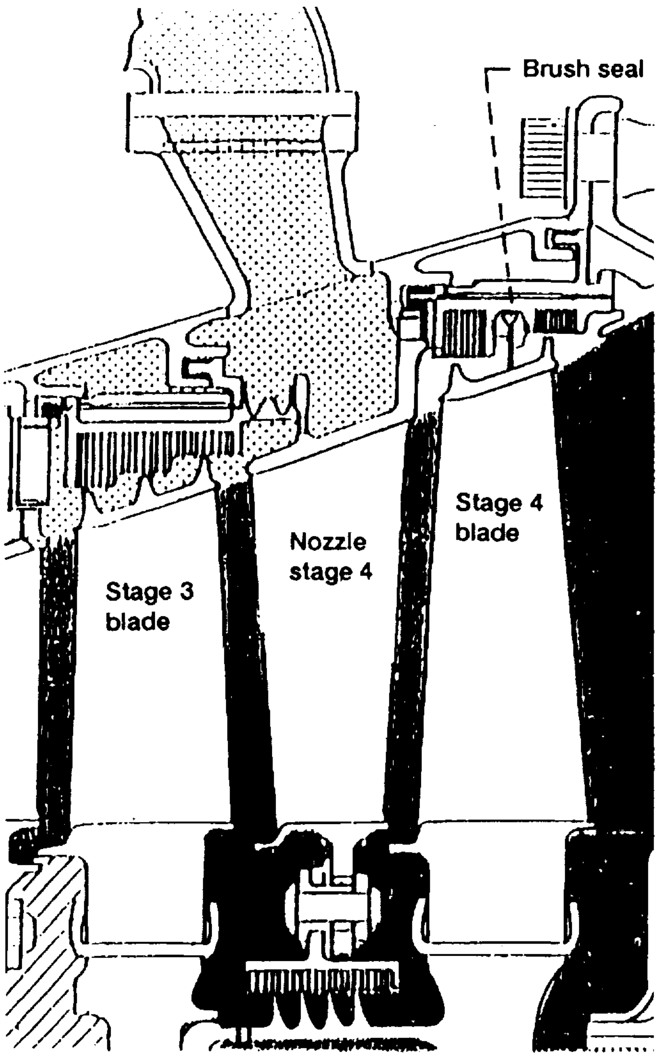
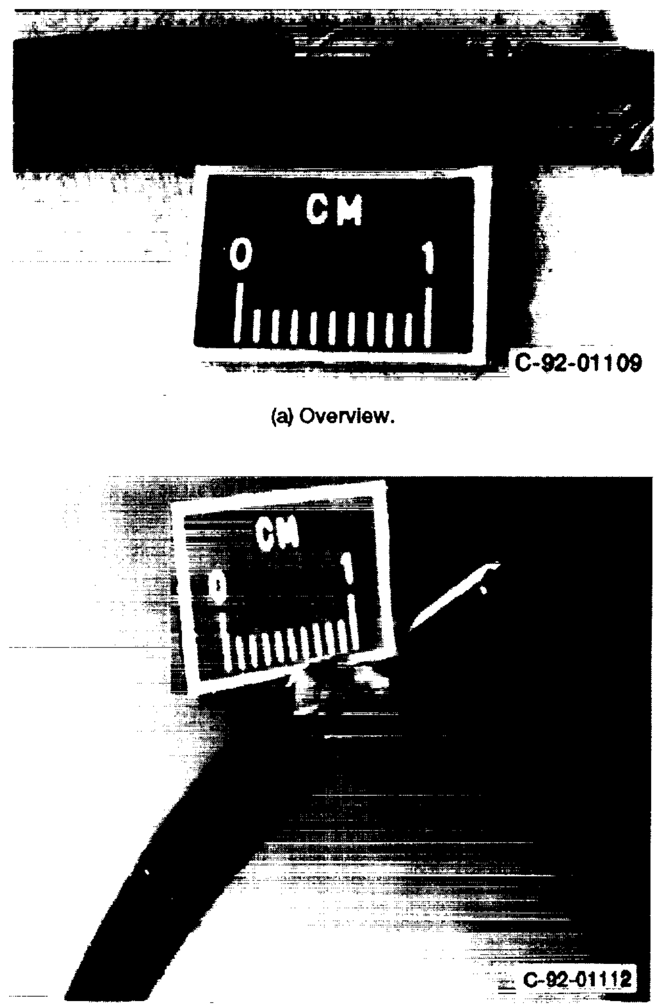


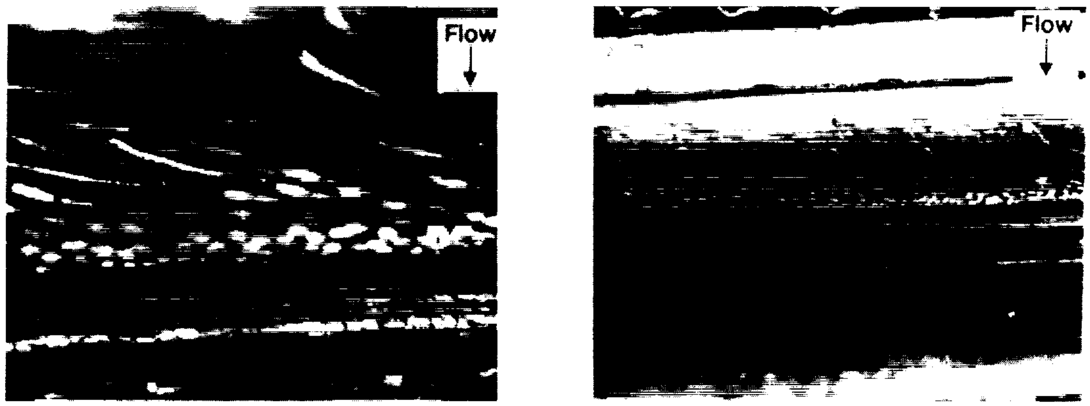
Figure 1.—Schematic of power turbine. From reference 1.



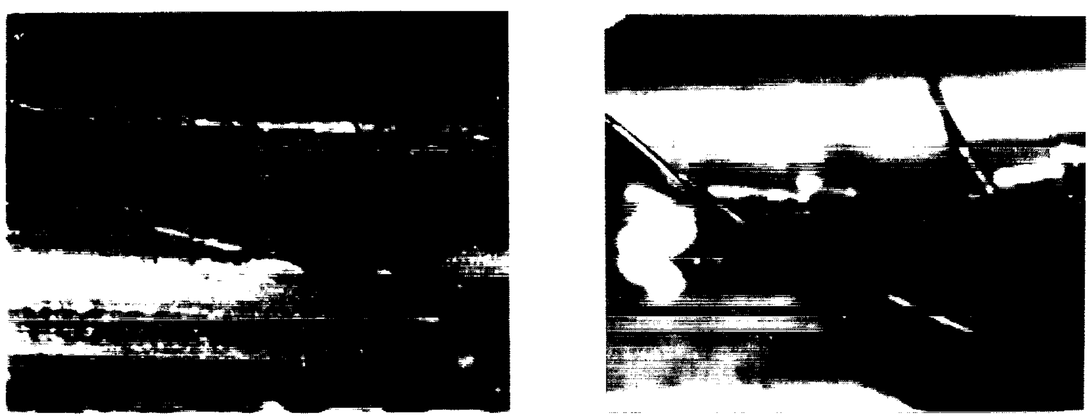
(a) Overview.

(b) Cross section.

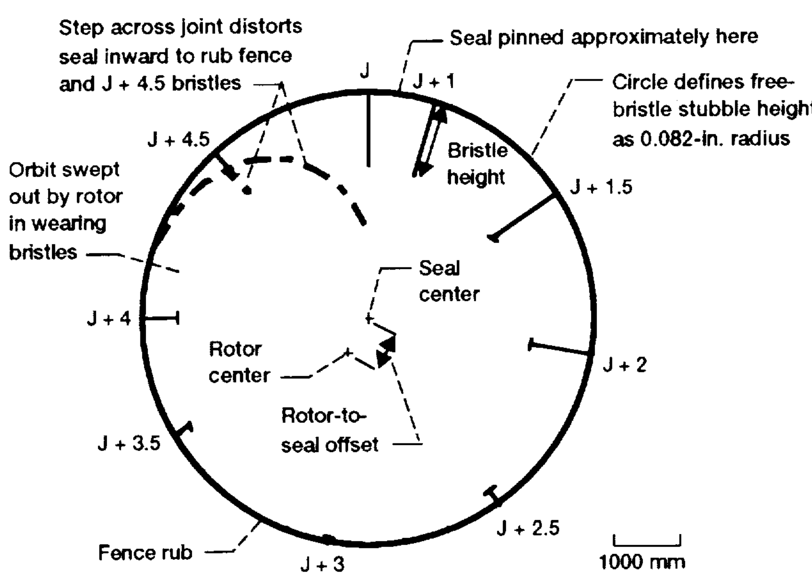
Figure 2.—Split-ring brush seal. From reference 1.



(i) Wear track and fence rub.



(ii) Joint wear track.



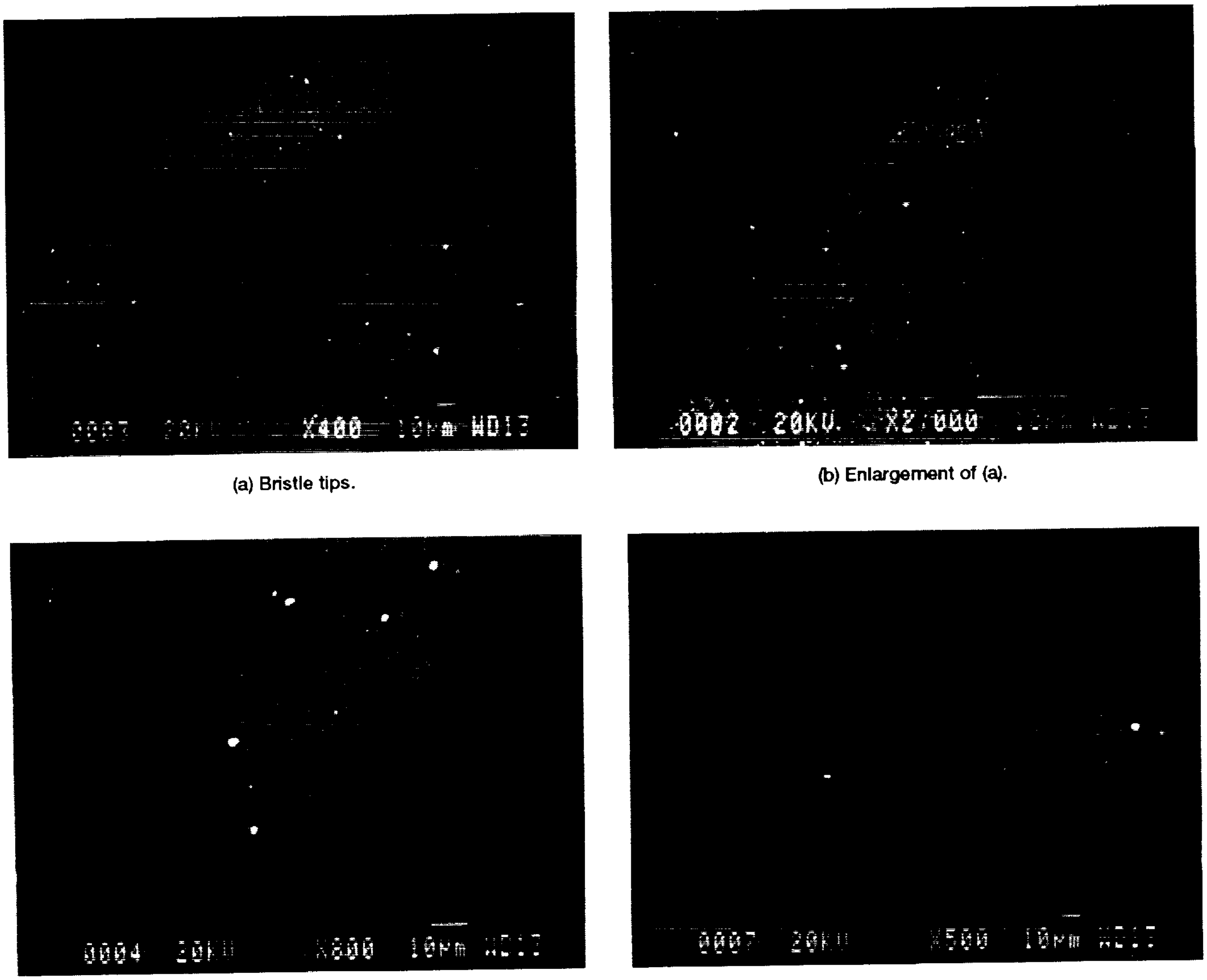
(iii) Bristle heights.

(a) Bristle heights, wear track and fence rub, and joint wear track.

Figure 3.—Post-test turbine shroud wear pattern. From reference 1.

(b) Rotor scars.

Figure 3.—Concluded.



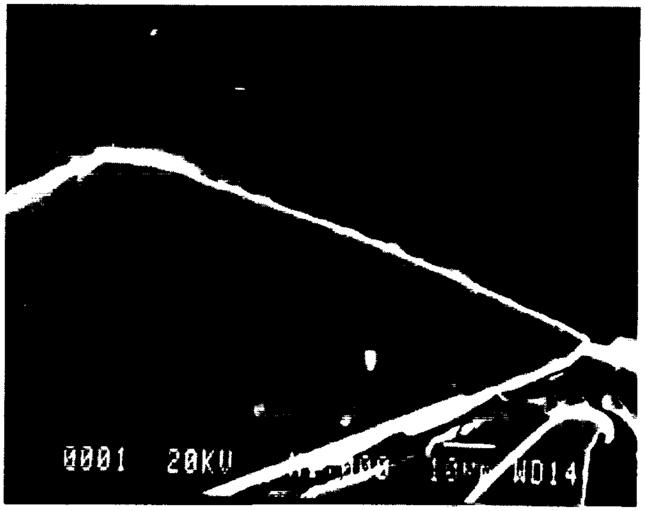
(a) Bristle tips.

(b) Enlargement of (a).

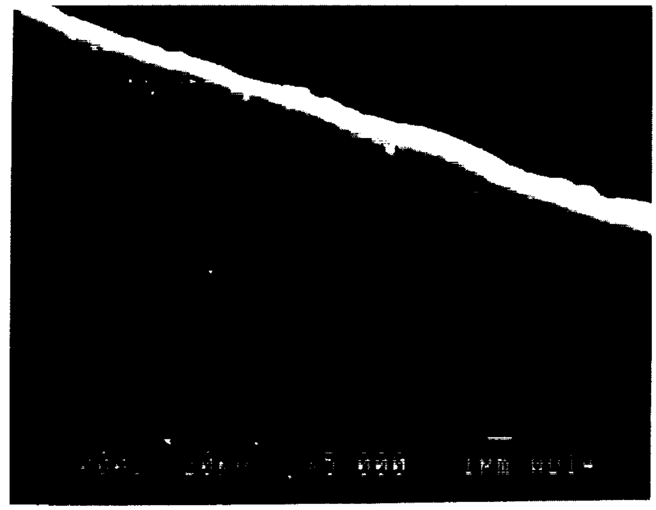
(c) Worn bristle tip.

(d) Tip with possible transfer material.

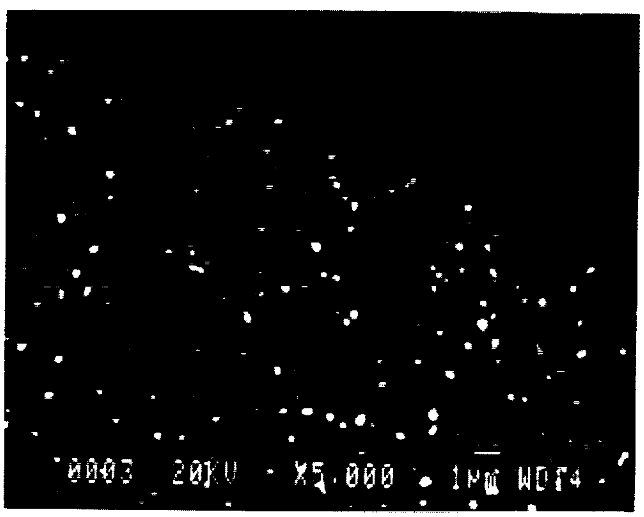
Figure 4.—Post-test analysis of bristles cut from brush seal, showing irregular tips.



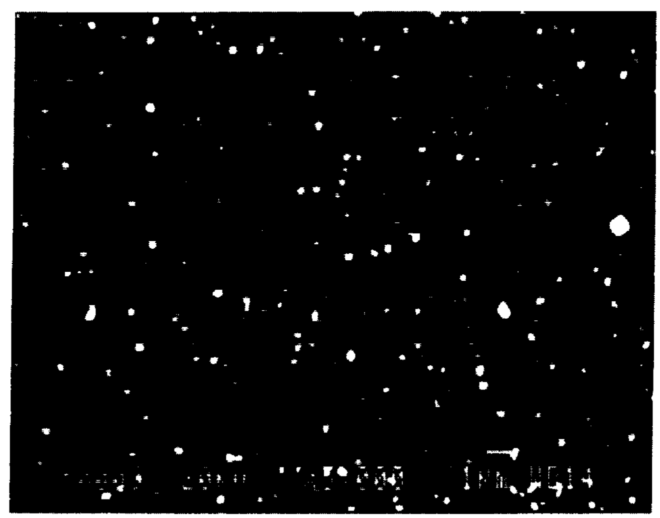
(a) Bristle tip.



(b) Enlargement of bristle surface.

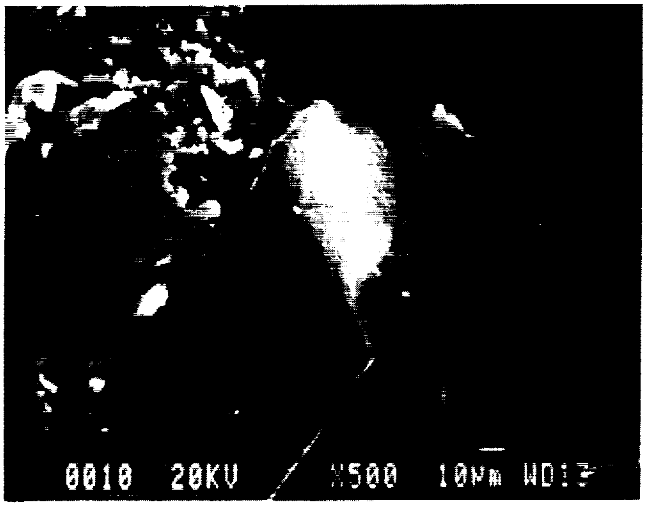


(c) Tungsten spots near interface.



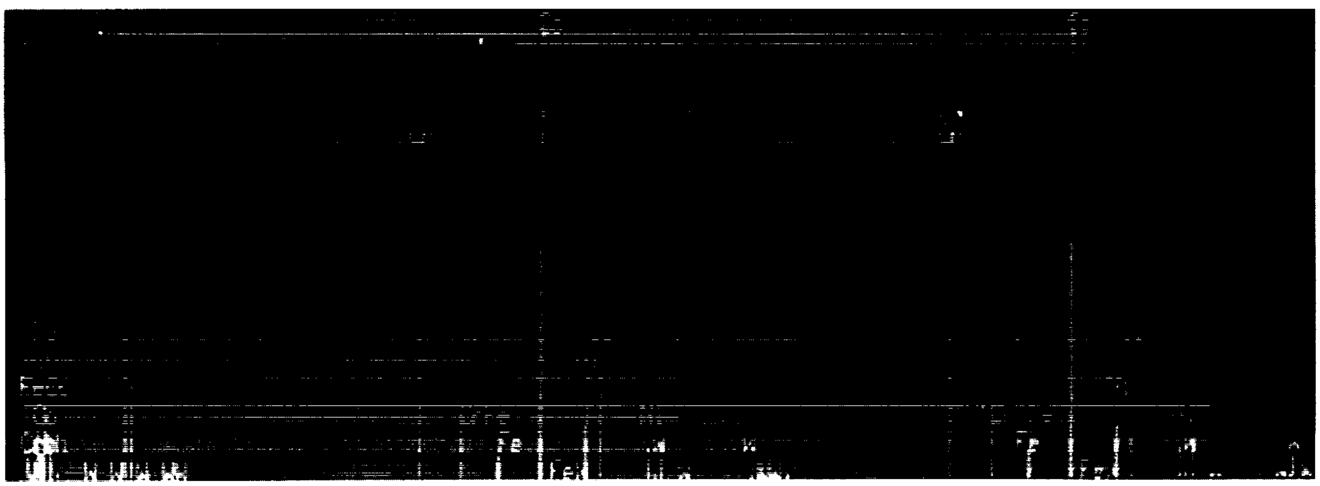
(d) Tungsten spots in interior.

Figure 5.—Etched surface structure, illustrating tungsten distribution.



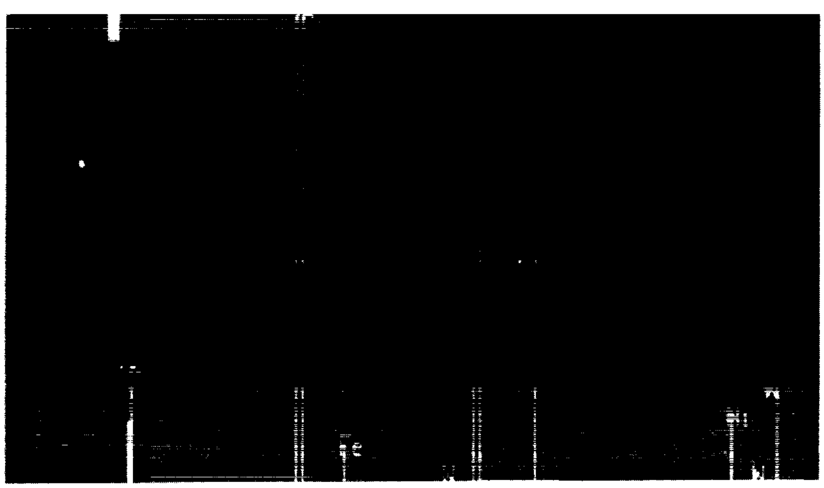
(a) Plan and end view.

(b) Tungsten distribution.



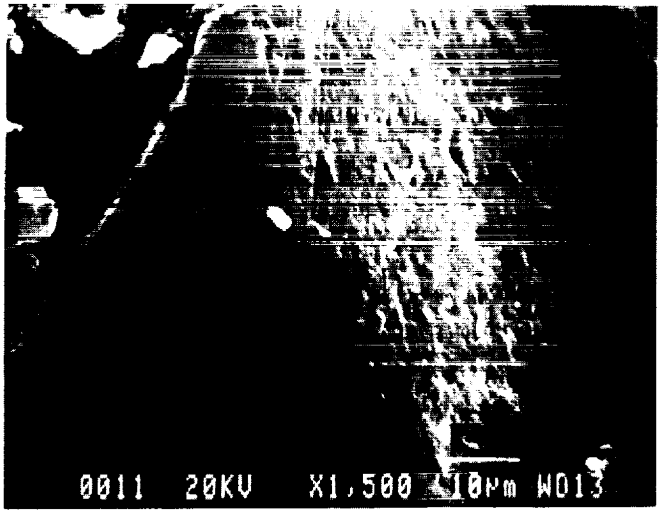
(c) Energy spectra.

(d) Selected region of (c).

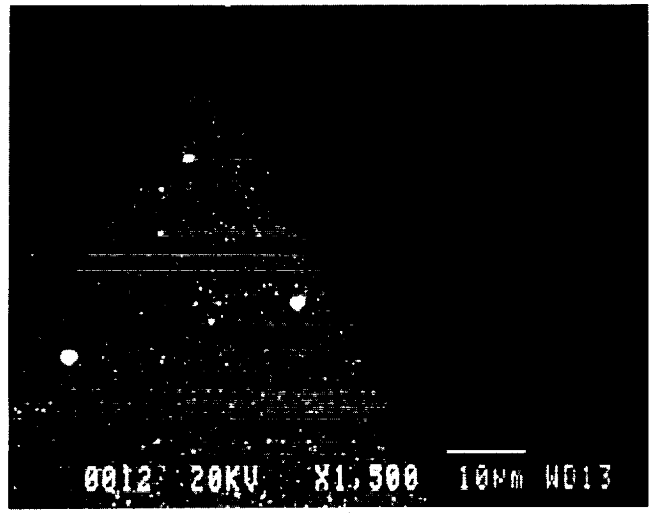


(e) Enhanced view of (d).

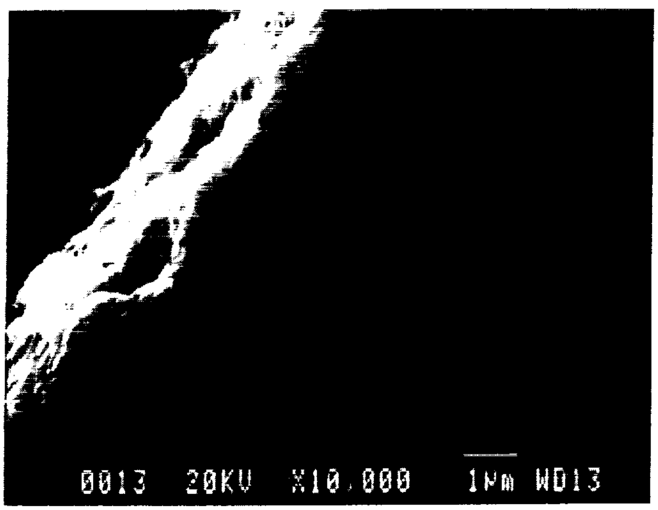
Figure 6.—Bristle tip wear surfaces, oxidation, and element composition.



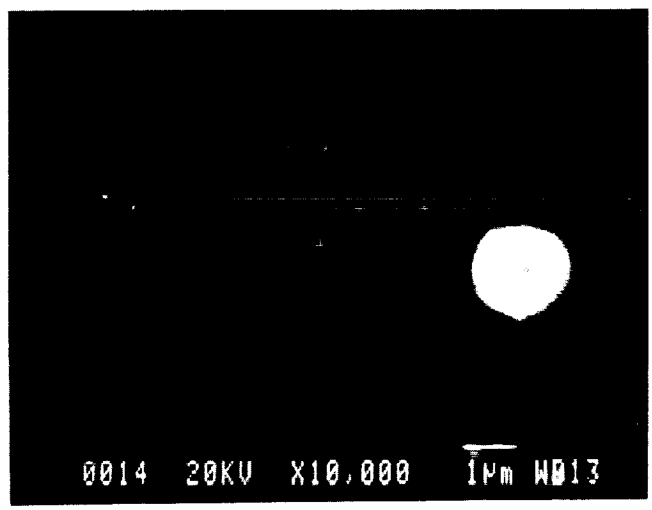
(a) Enlarged view of fig. 6(a).



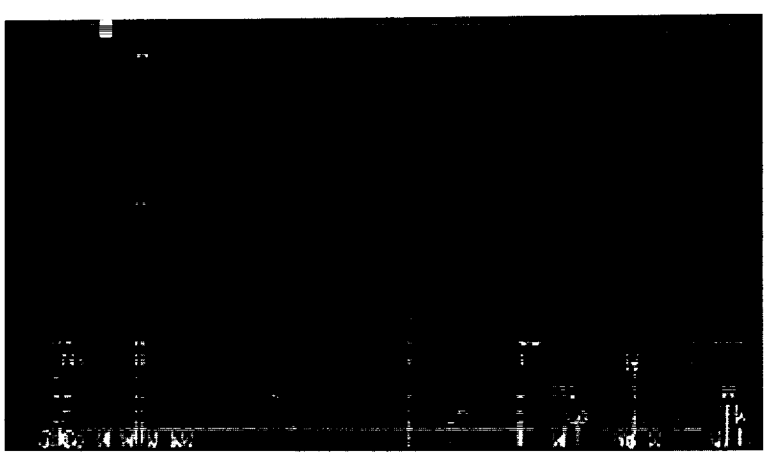
(b) Enlarged view of fig. 6(b).



(c) Further enlargement of fig. 6(a).

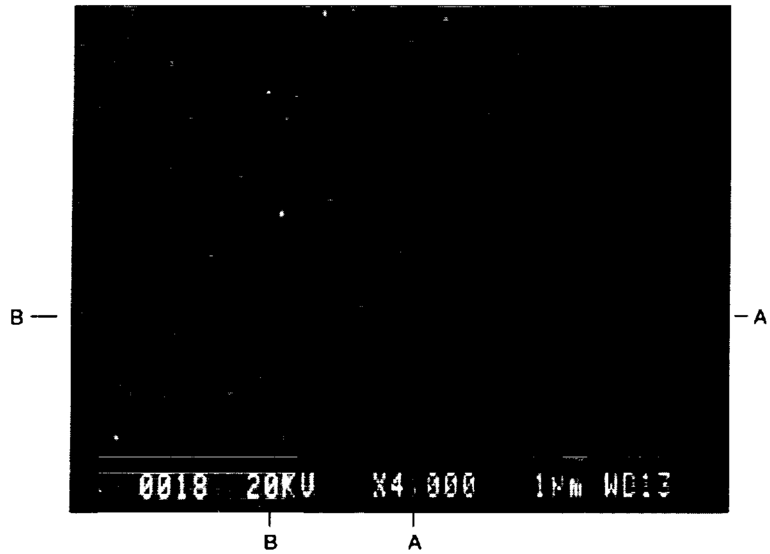


(d) Further enlargement of fig. 6(b).

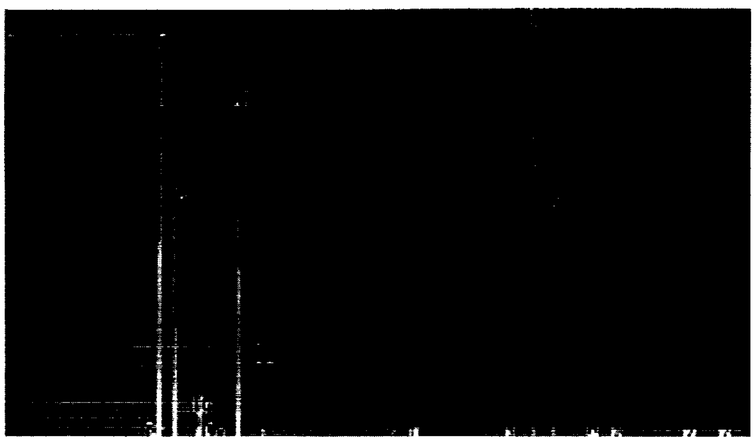


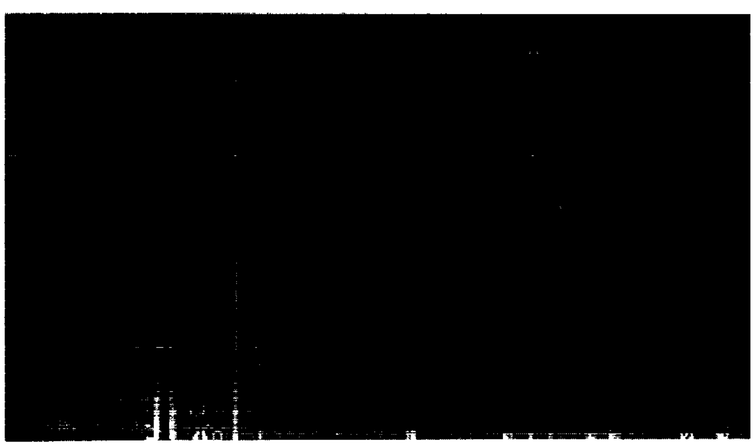
(e) Energy spectra of (d).

Figure 7.—Magnification of bristle tip wear surface and element composition.



(a) Oxide scale.

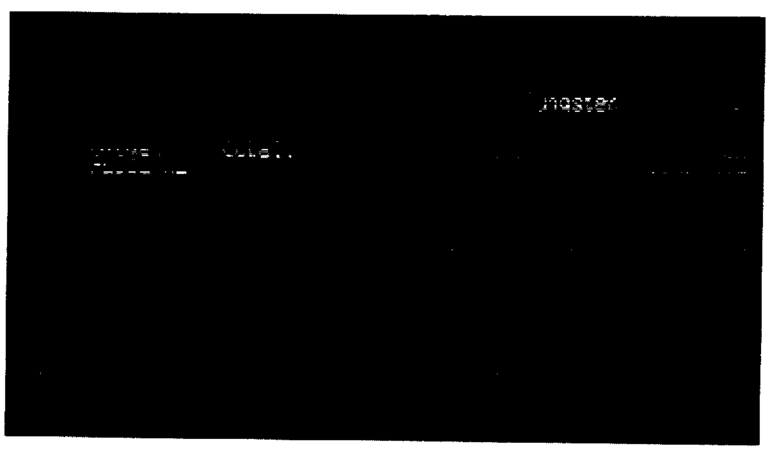

(i) Coordinates A–A.


(ii) Coordinates B–B.

(b) Energy spectra.

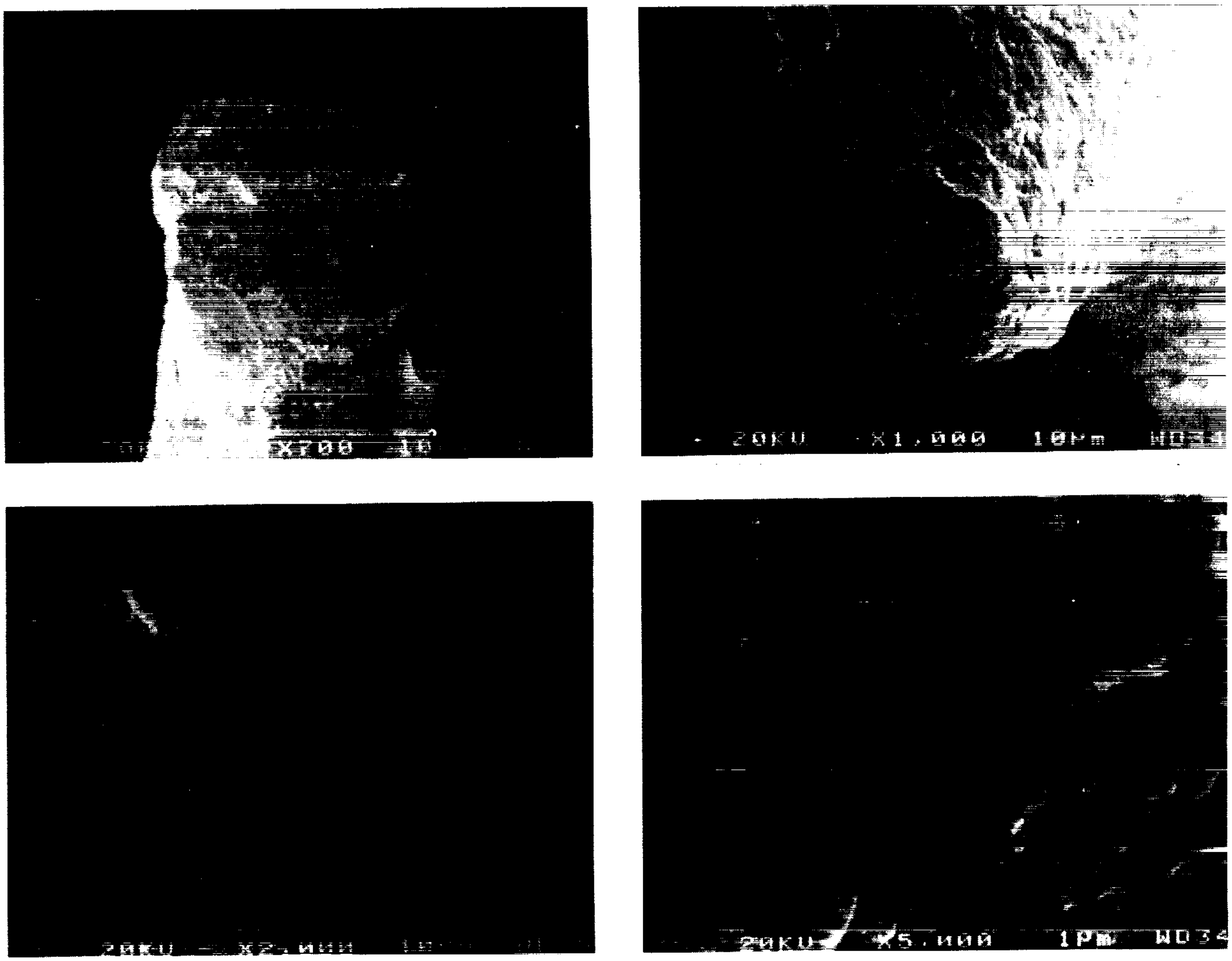
Figure 8.—Oxide scale on bristle.

(c) Energy spectra comparison (oxide to matrix).



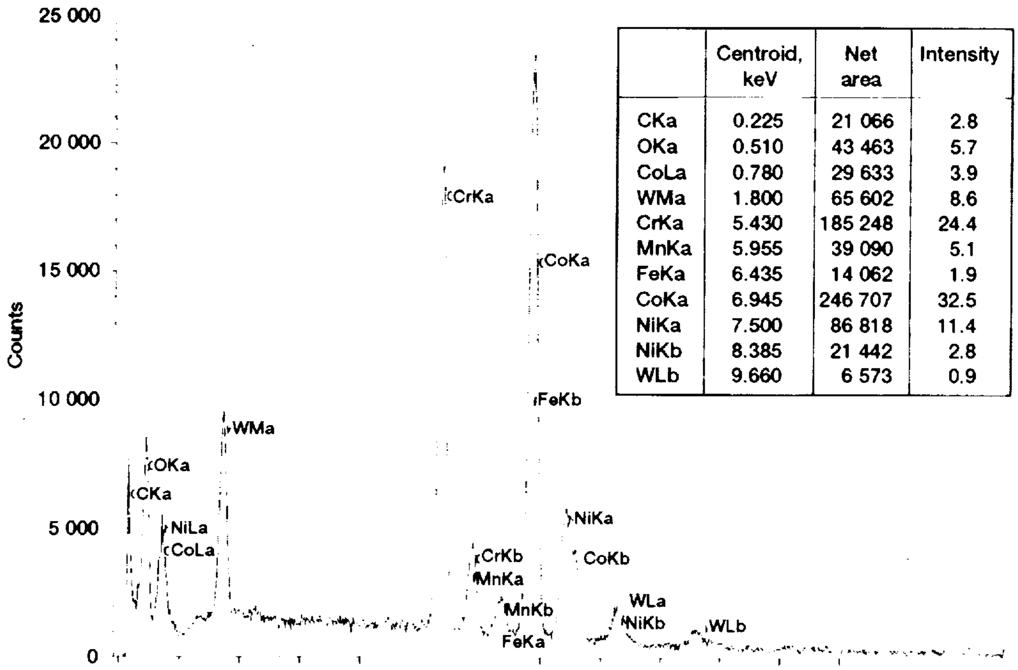
(d) Enlarged view of (c).

Figure 8.—Concluded.



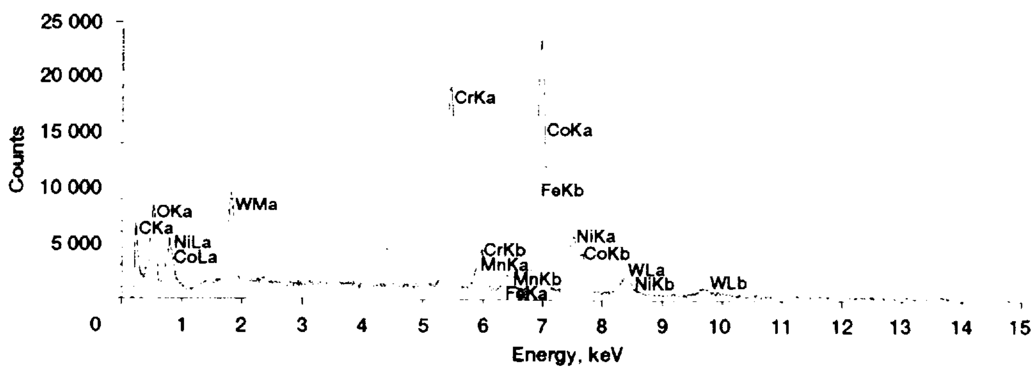
(a) Cut end. (b) Worn end, showing oxide formation.

Figure 9.—Bristle cut and worn ends.



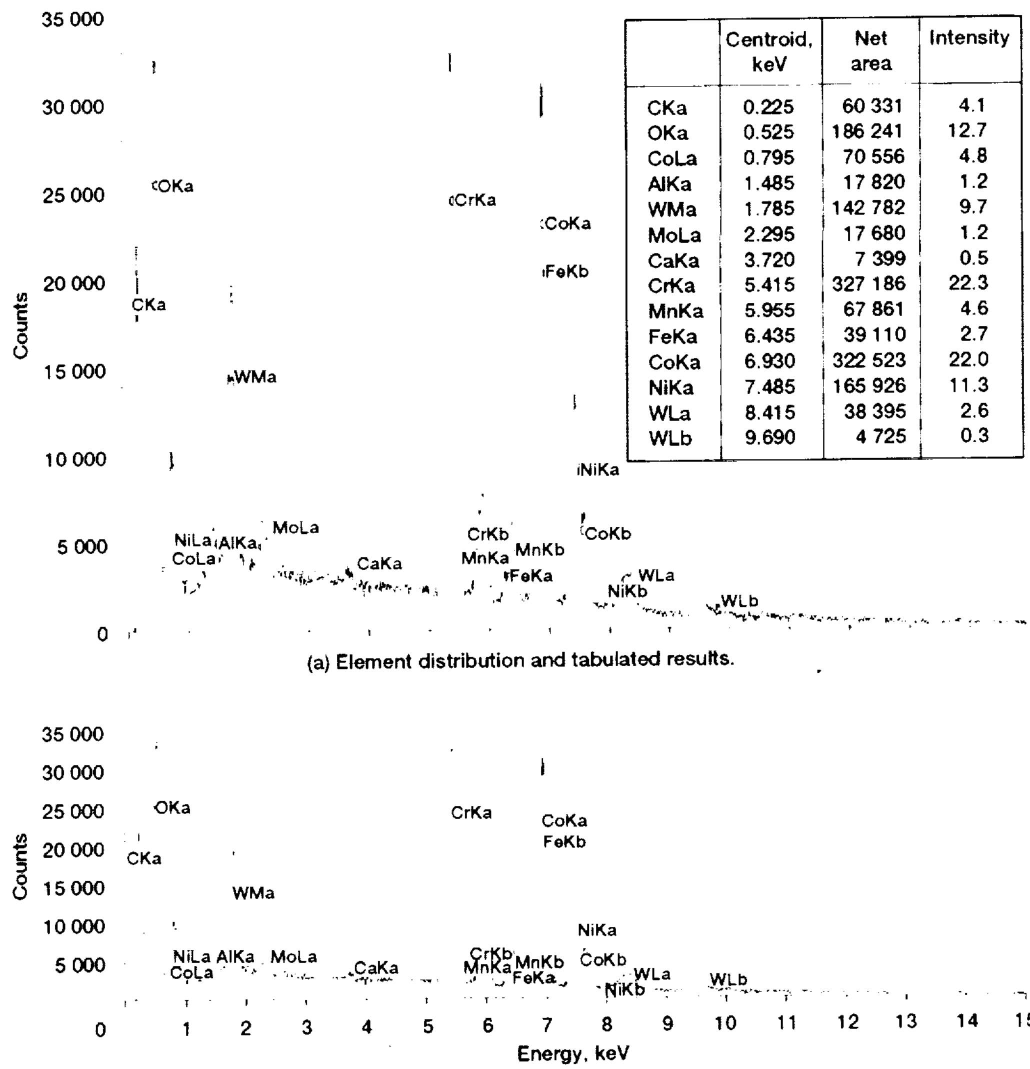
	Centroid, keV	Net area	Intensity
CKa	0.225	21 066	2.8
OKa	0.510	43 463	5.7
CoLa	0.780	29 633	3.9
WMa	1.800	65 602	8.6
CrKa	5.430	185 248	24.4
MnKa	5.955	39 090	5.1
FeKa	6.435	14 062	1.9
CoKa	6.945	246 707	32.5
NiKa	7.500	86 818	11.4
NiKb	8.385	21 442	2.8
WLb	9.660	6 573	0.9

(a) Element distribution and tabulated results.



(b) Rescaled distribution.

Figure 10.—Composition of bristle cut end. Beam current, 0.3 mA; count time, 200 s; accelerating potential, 20 kV; beam spot magnification, 2000.



	Centroid, keV	Net area	Intensity
CKa	0.225	60 331	4.1
OKa	0.525	186 241	12.7
CoLa	0.795	70 556	4.8
AlKa	1.485	17 820	1.2
WMa	1.785	142 782	9.7
MoLa	2.295	17 680	1.2
CaKa	3.720	7 399	0.5
CrKa	5.415	327 186	22.3
MnKa	5.955	67 861	4.6
FeKa	6.435	39 110	2.7
CoKa	6.930	322 523	22.0
NiKa	7.485	165 926	11.3
WLa	8.415	38 395	2.6
WLb	9.690	4 725	0.3

(a) Element distribution and tabulated results.

(b) Rescaled distribution.

Figure 11.—Composition of bristle worn end. Beam current, 0.3 mA; count time, 200 s; accelerating potential, 20 kV; beam spot magnification, 5000.

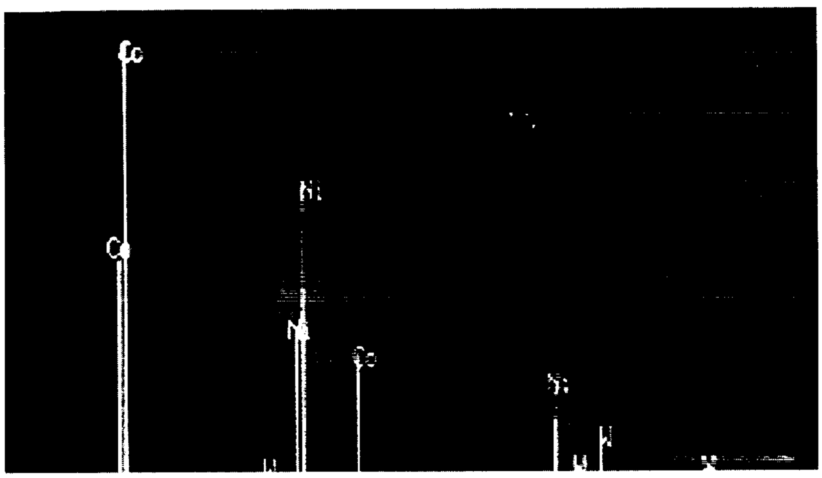
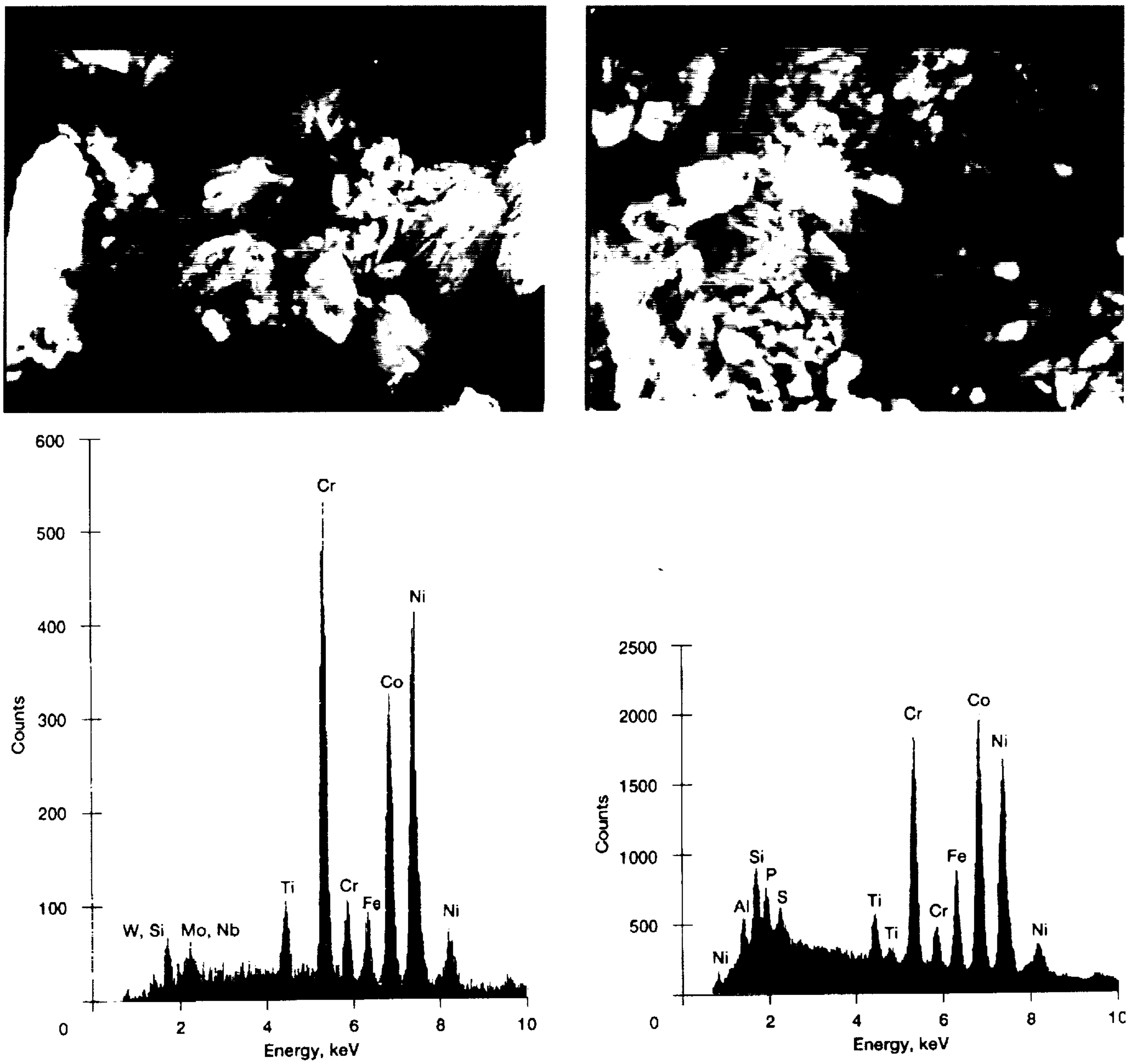


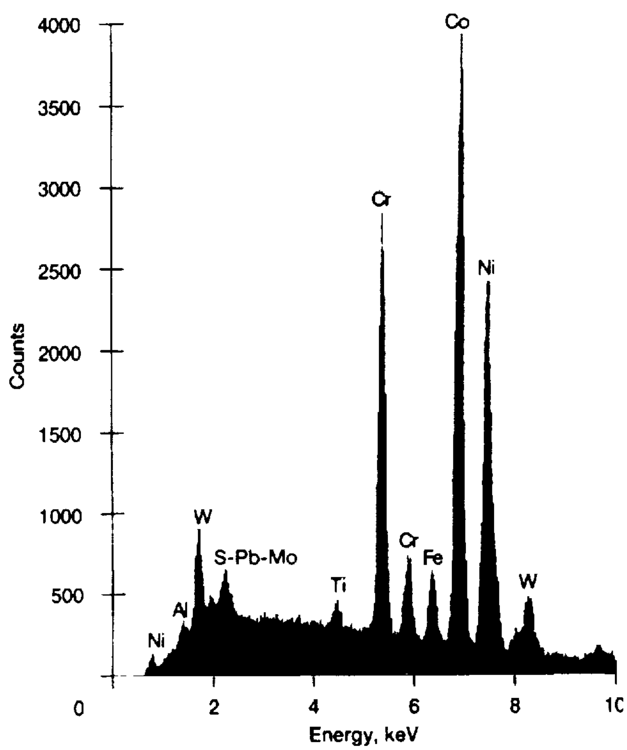
Figure 12.—Material transfer from René 80 rotor to Haynes 25 bristle.



(a) Particle WS1A.

(b) Particle WS111A.

Figure 13.—Typical element spectra of post-test material scraped from René 80 rotor.



(c) Particle WSVA.

Figure 13.—Concluded.

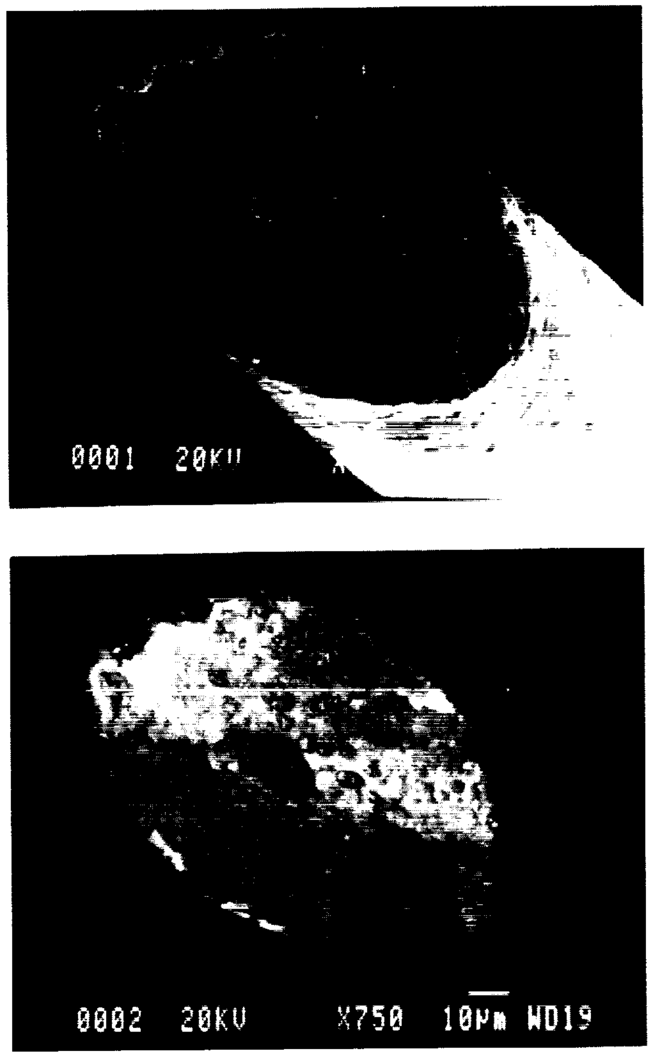
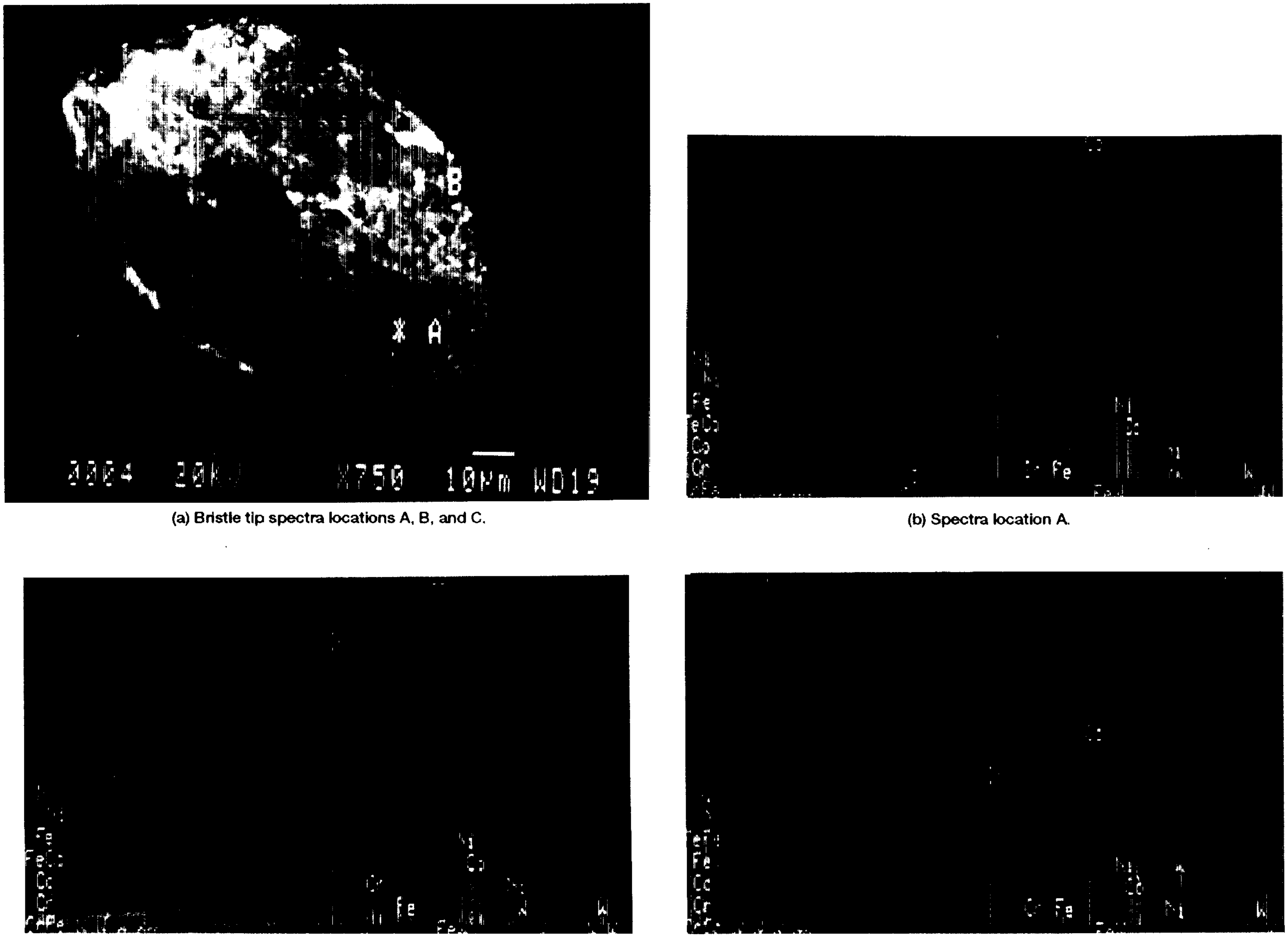


Figure 14.—Material transfer at bristle tip.



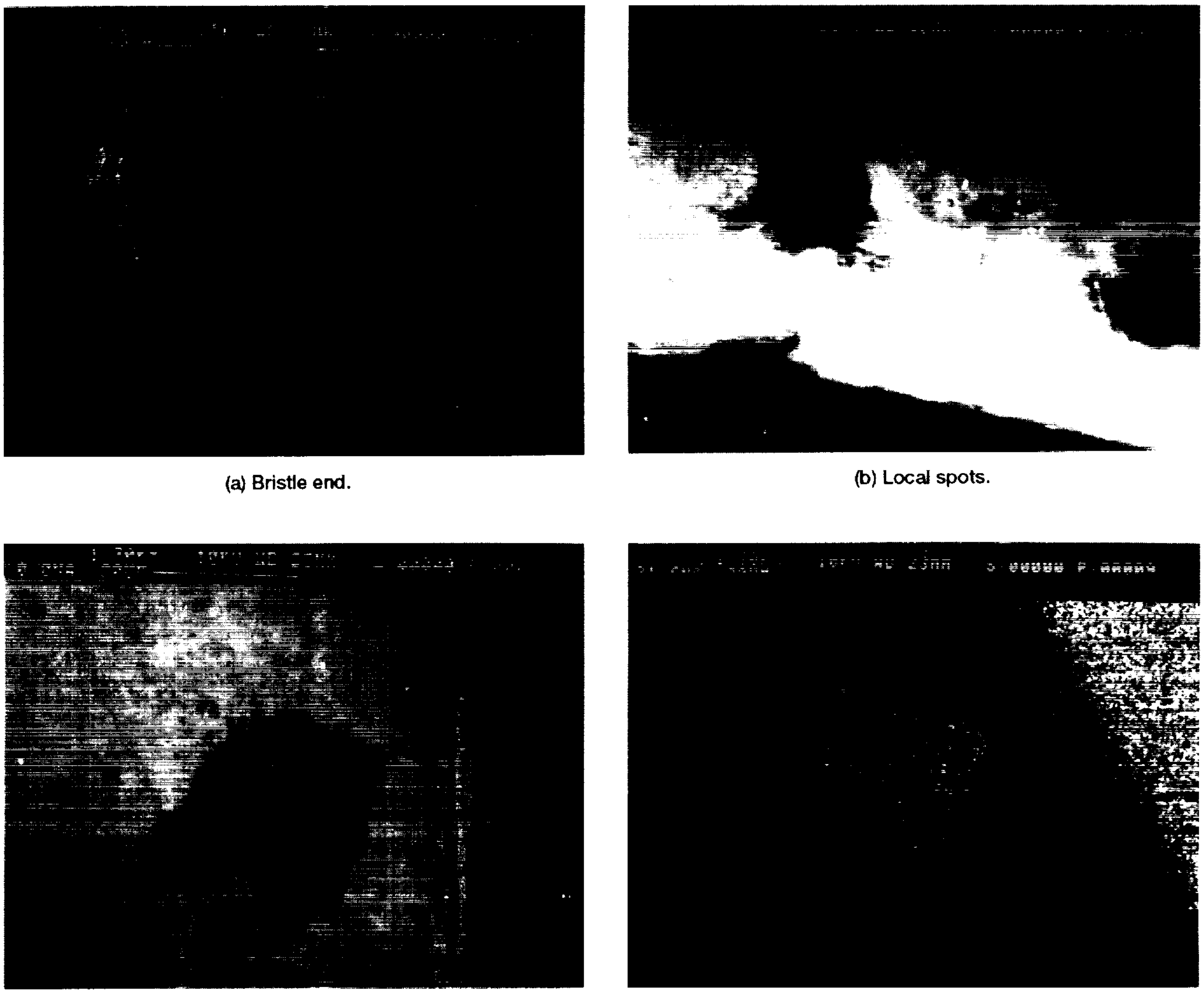
(a) Bristle tip spectra locations A, B, and C.

(b) Spectra location A.

(c) Spectra location B.

(d) Spectra location C.

Figure 15.—Variations in tungsten over bristle tip.



(a) Bristle end.

(b) Local spots.

(c) Surface spot.

(d) Carbon dots of (c).

Figure 16.—Carbon distribution within spot on bristle tip.

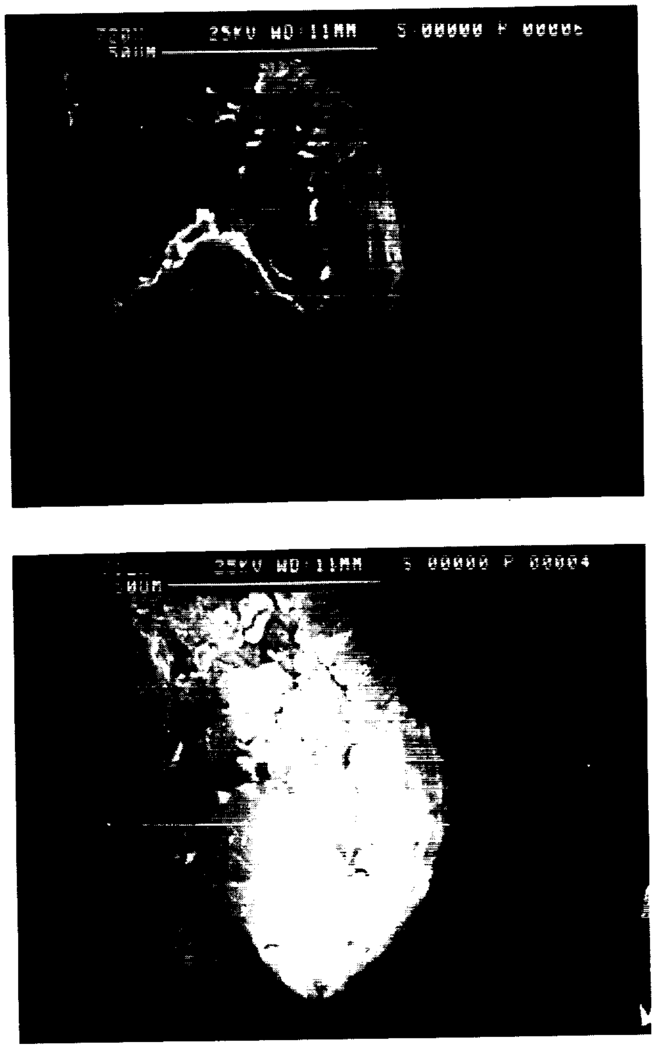
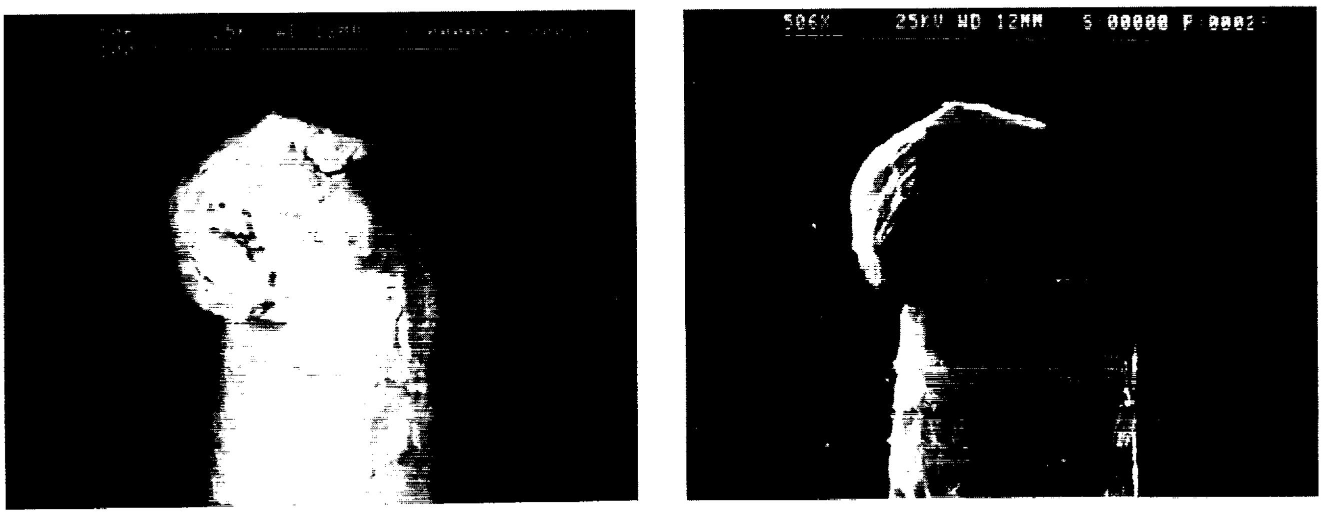
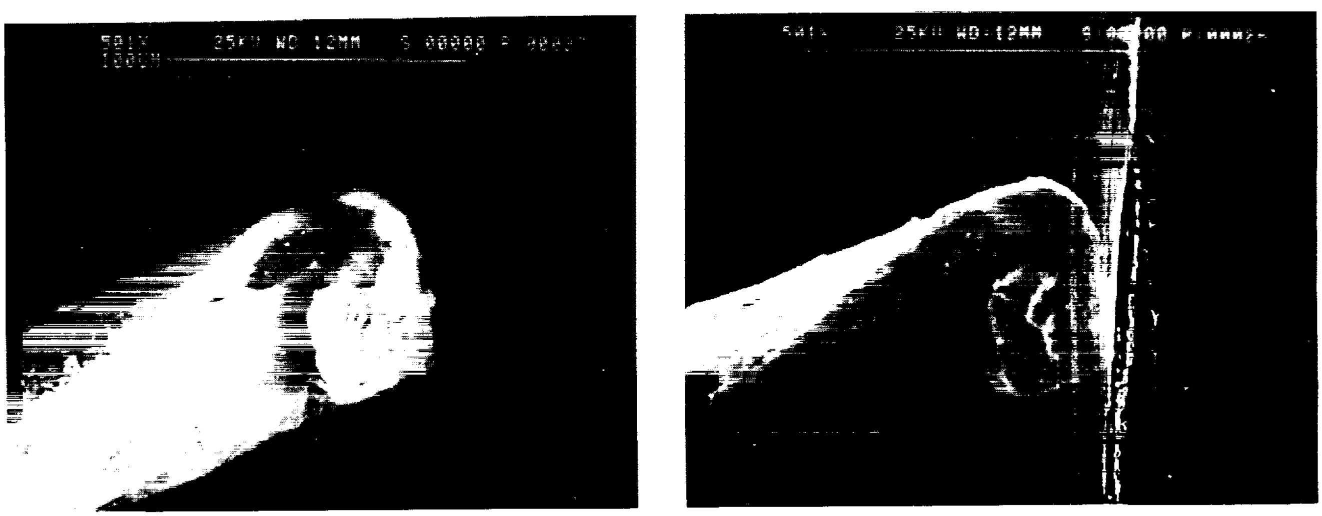


Figure 17.—Typical bristle tip collected in T-700 exhaust duct.



(a) Bristle tip 1 (two exposures).



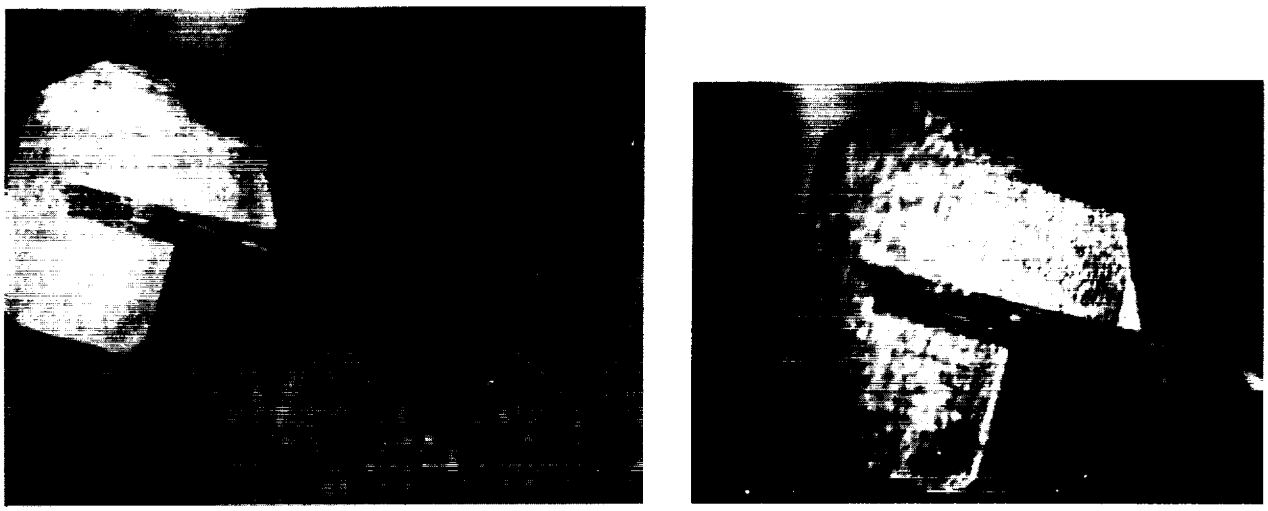
(b) Bristle tip 2 (two exposures).

Figure 18.—Typical bristle tip collected in T-700 exhaust duct, showing possible rubbed and quenched interface.

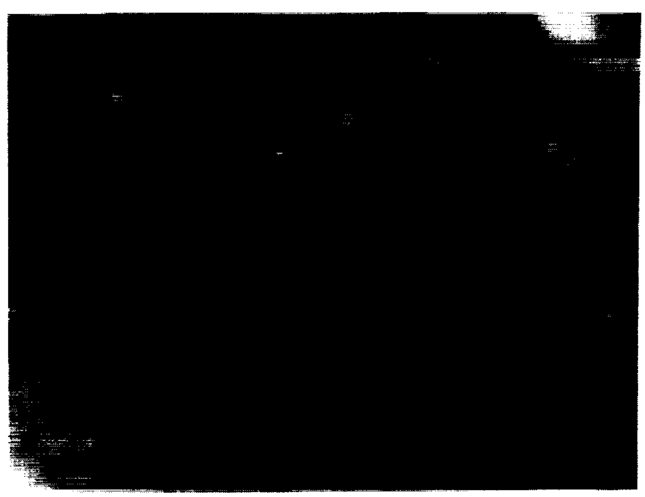
(a) Section 1.

(b) Section 2.

Figure 19.— Bristle smearing (mudflat cracks) characteristic of rub interface.

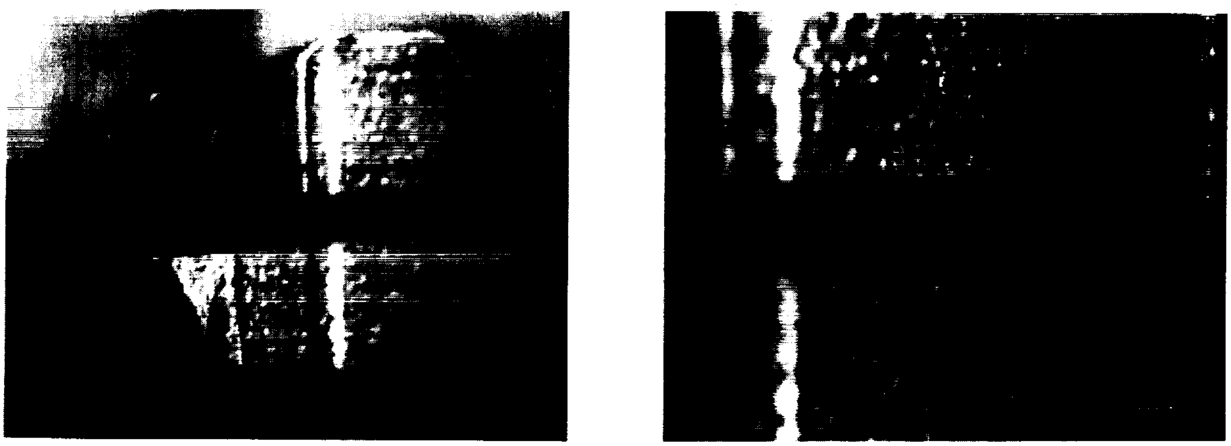


(a) Overview of bristles (seal section 1).

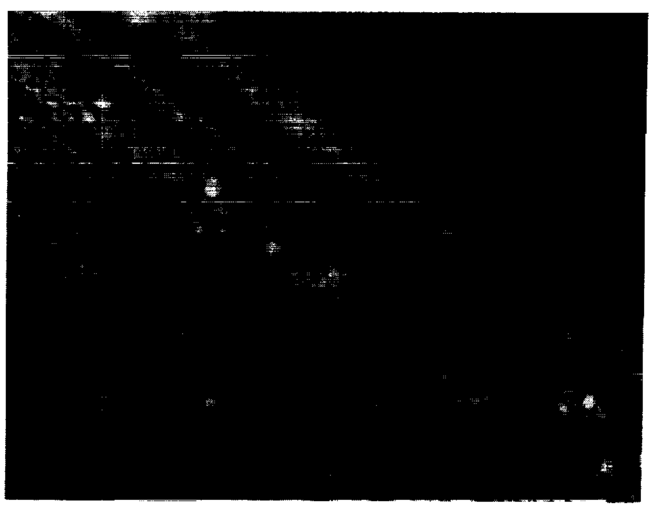


(b) Section of brush seal fence surface.

Figure 20.—Sets of information for brush segment 1.



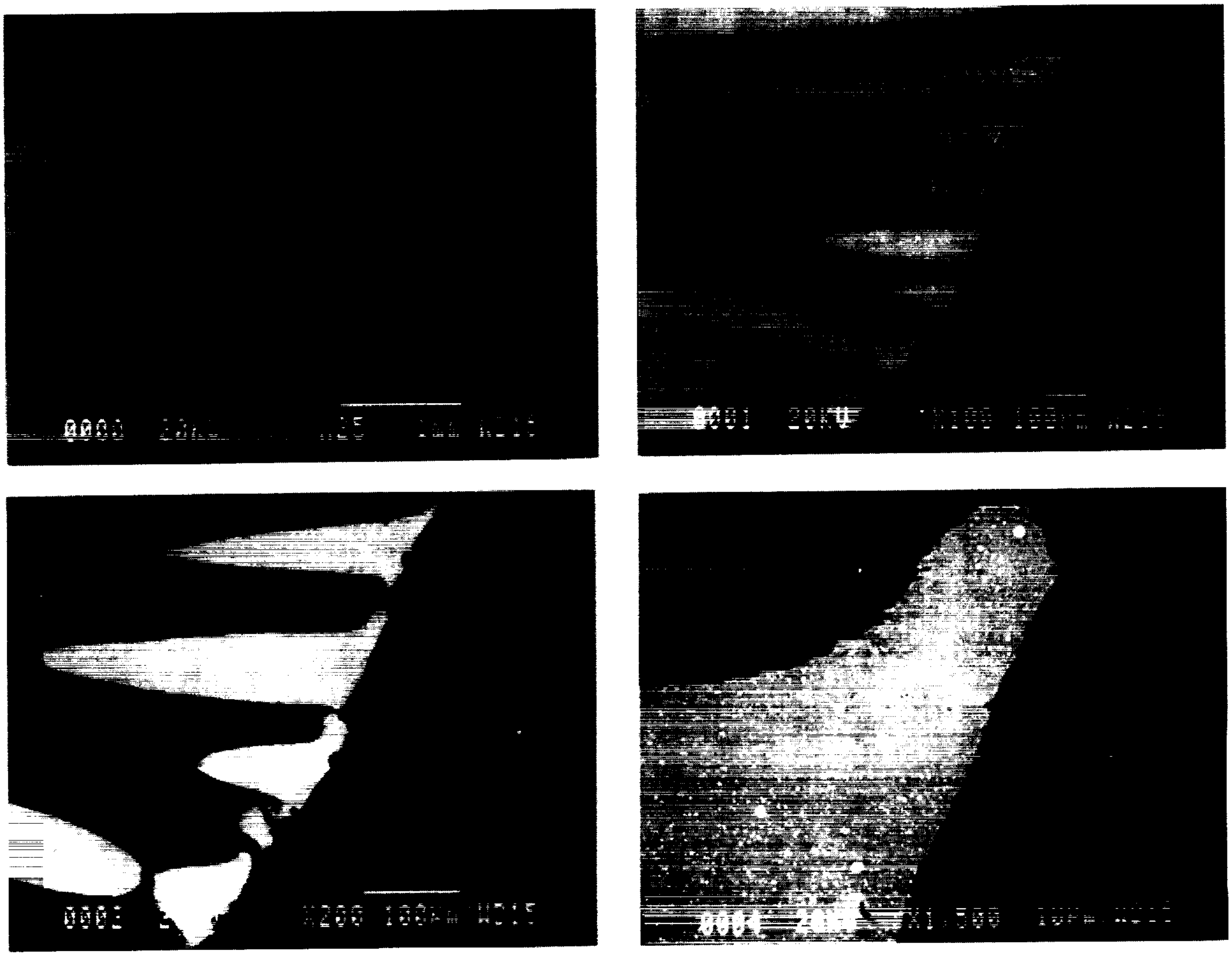
(a) Overview of bristles (seal section 2).



(I) Overview.

(b) Section of brush seal fence surface.

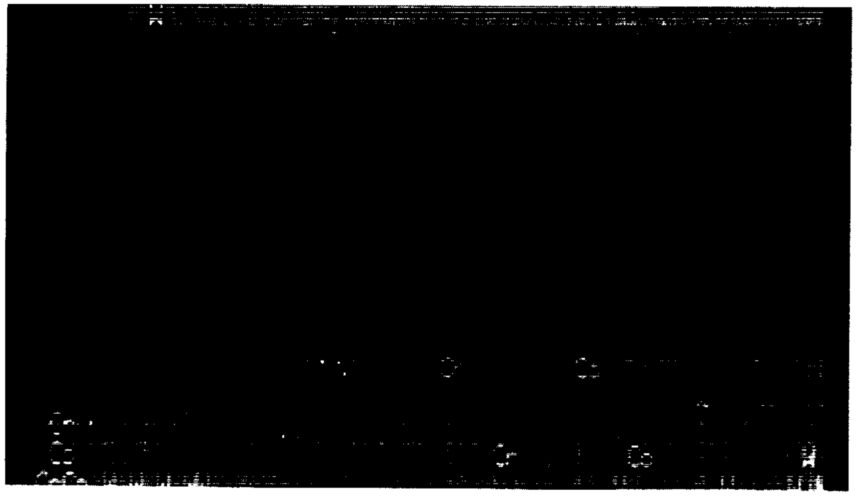
Figure 21.—Sets of information for brush segment 2.



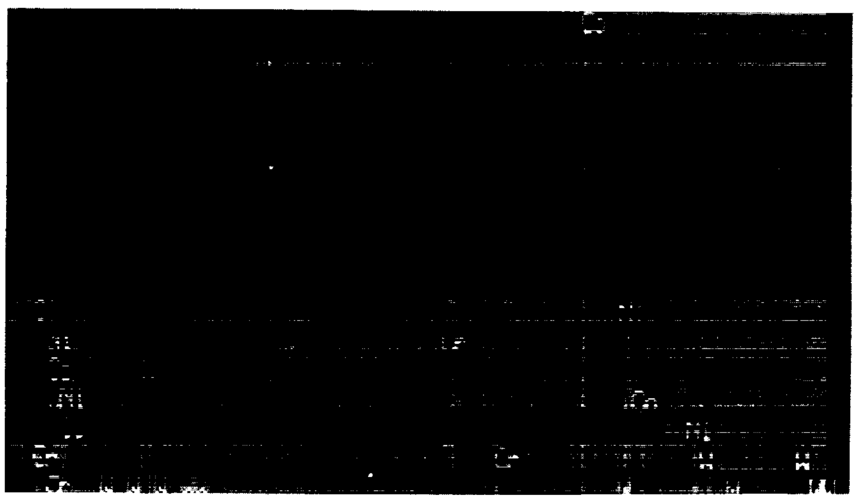
(ii) Enlargements of section view.

(b) Concluded.

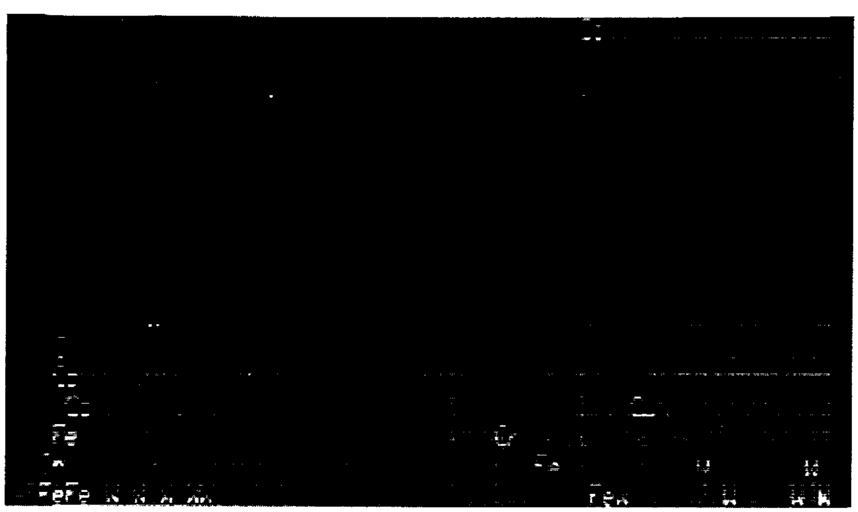
Figure 21.—Continued.



(i) White spot.



(ii) Oxide.

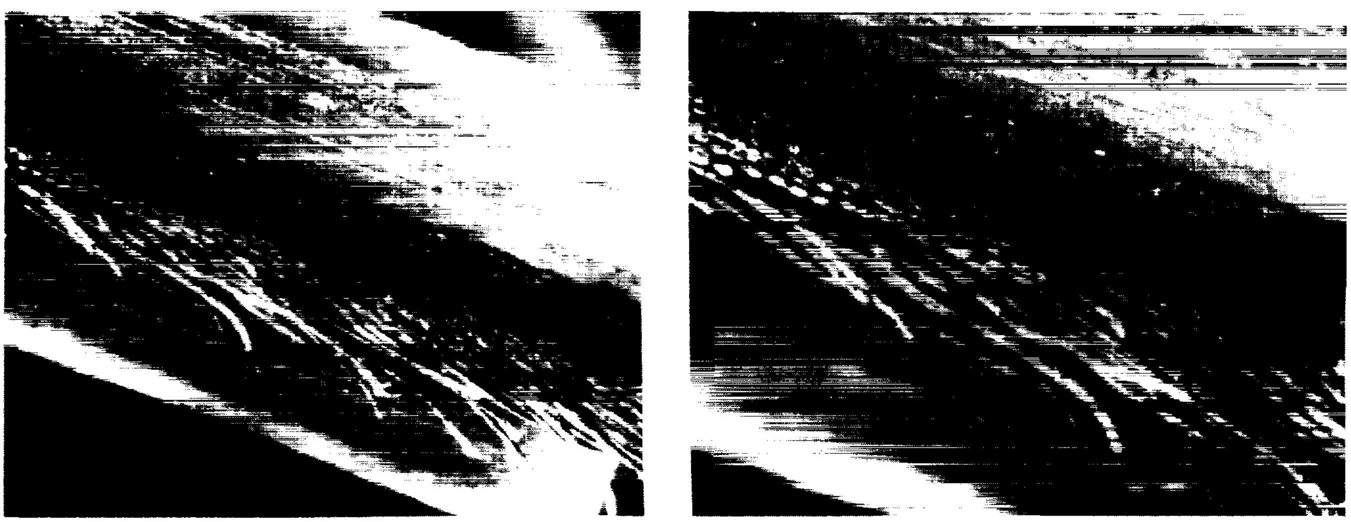


(iii) Matrix.

(c) Sets of element traces.

Figure 21.—Concluded.

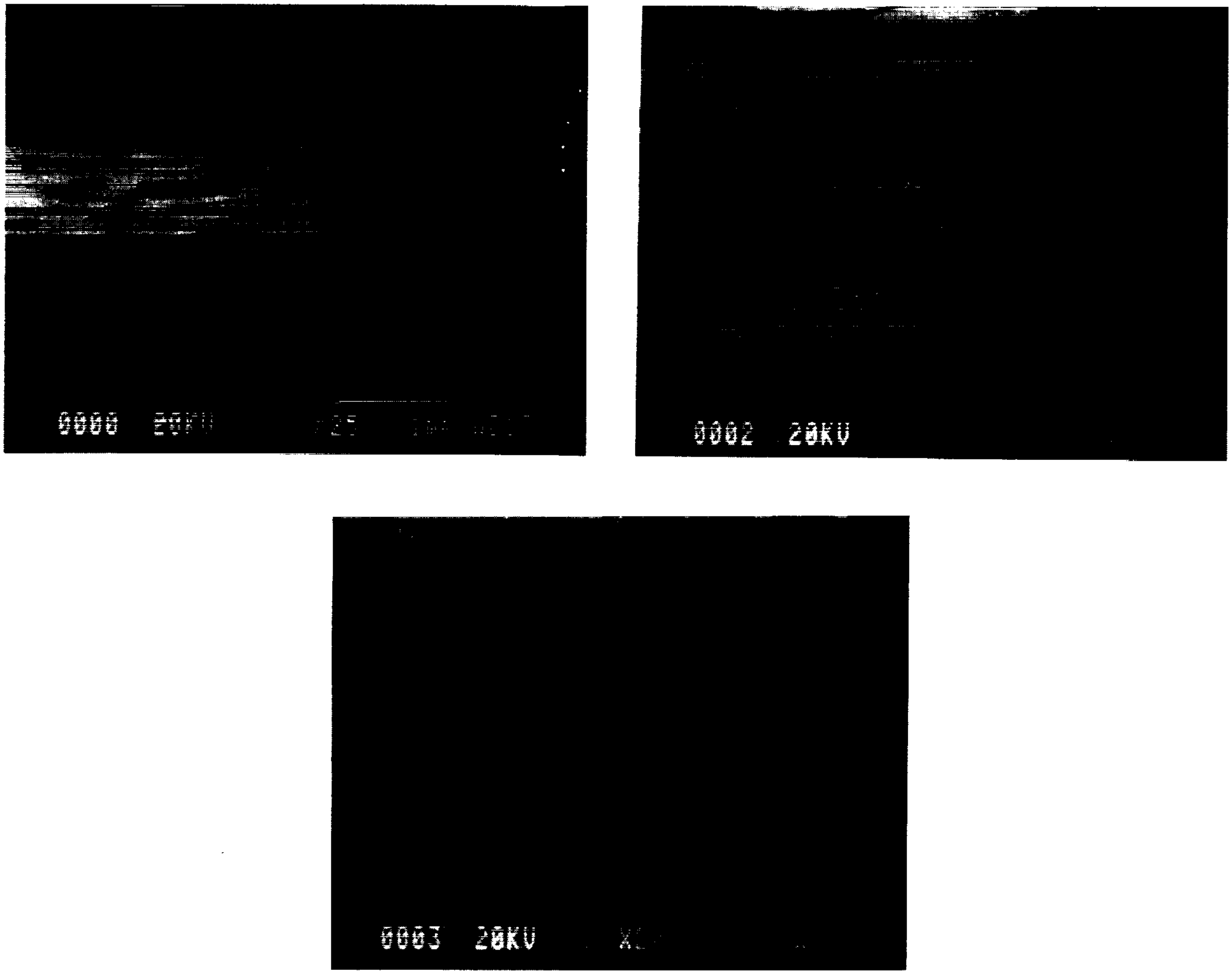
(a) Overview of bristles (seal section 3).



(i) Overview.

(b) Section of brush seal.

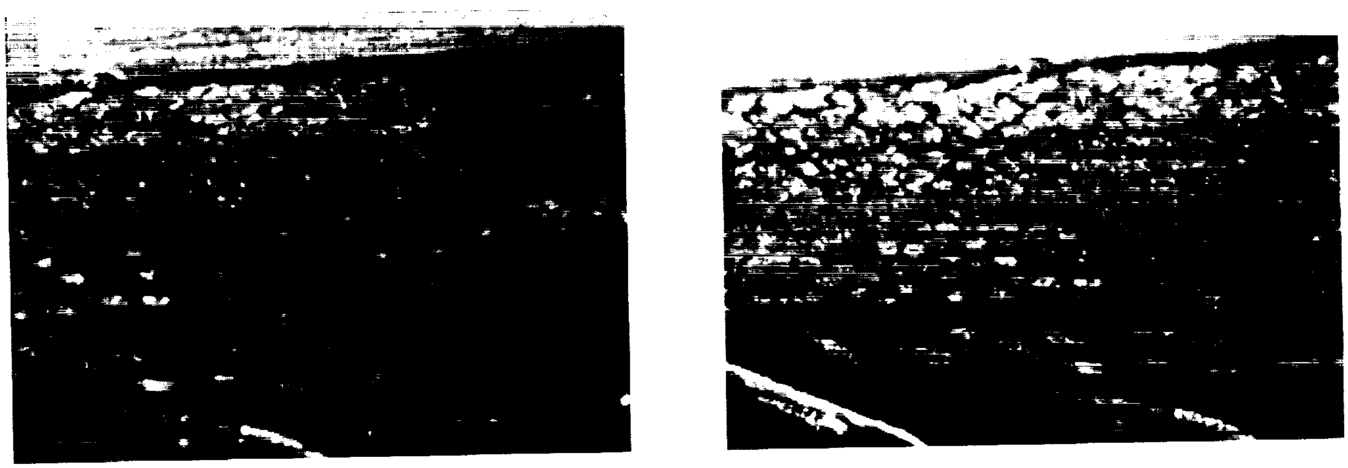
Figure 22.—Sets of information for brush segment 3.



(ii) Enlargement of section view.

(b) Continued.

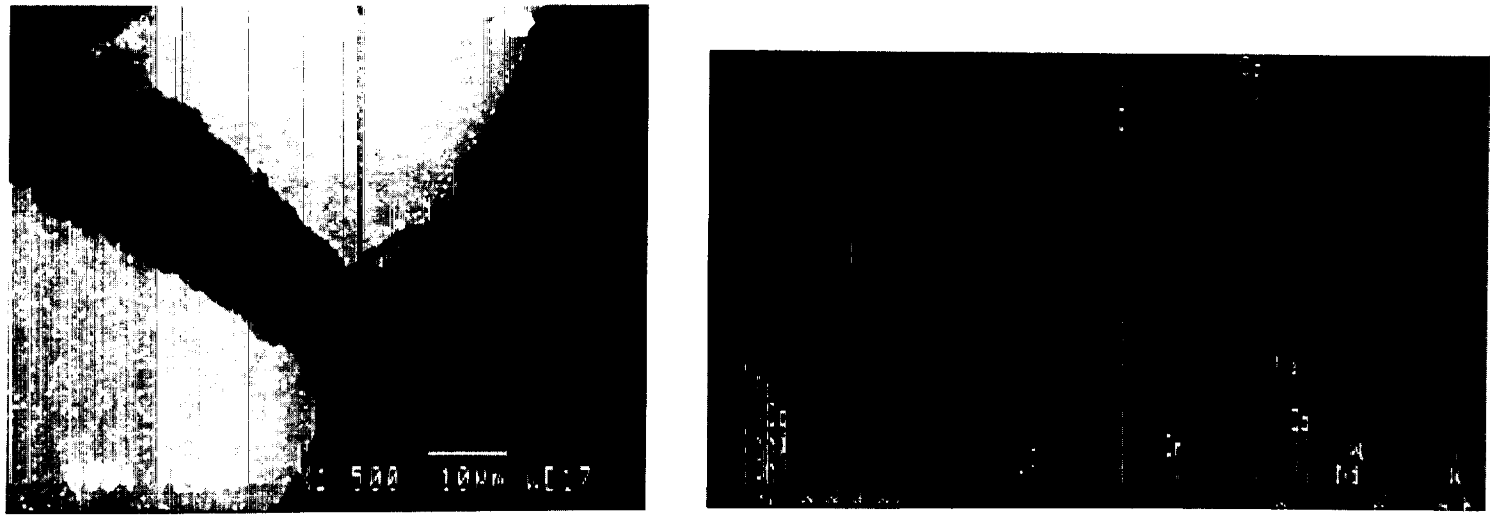
Figure 22.—Continued.



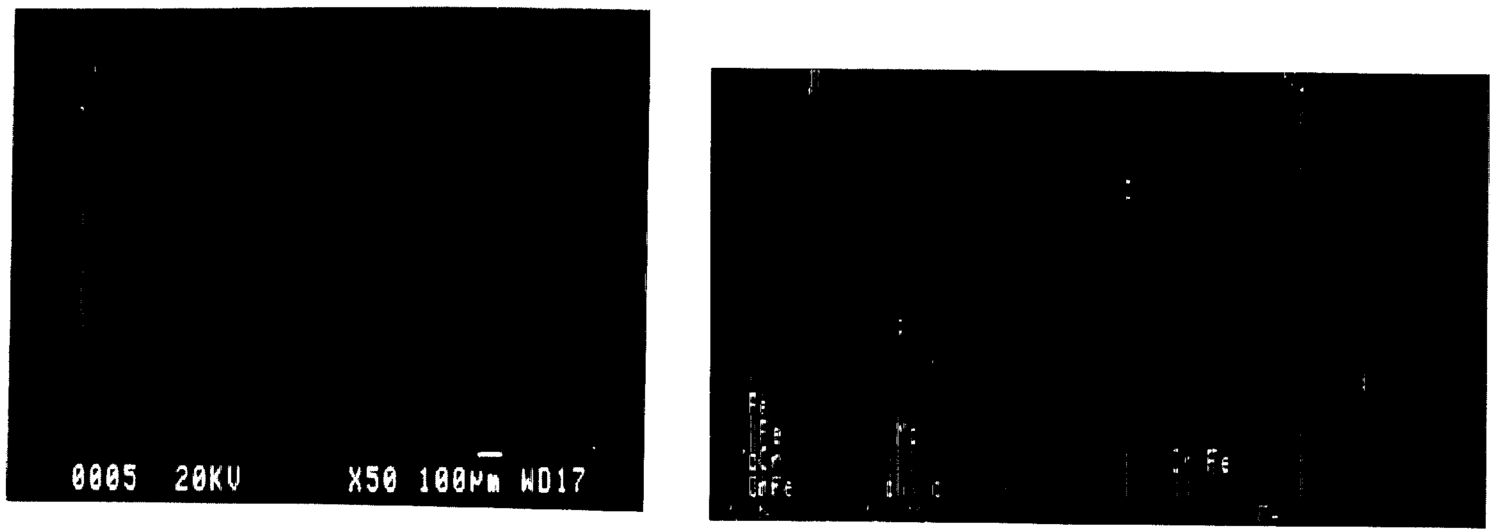
(iii) Enlargement of (i).

(b) Concluded.

Figure 22.—Continued.



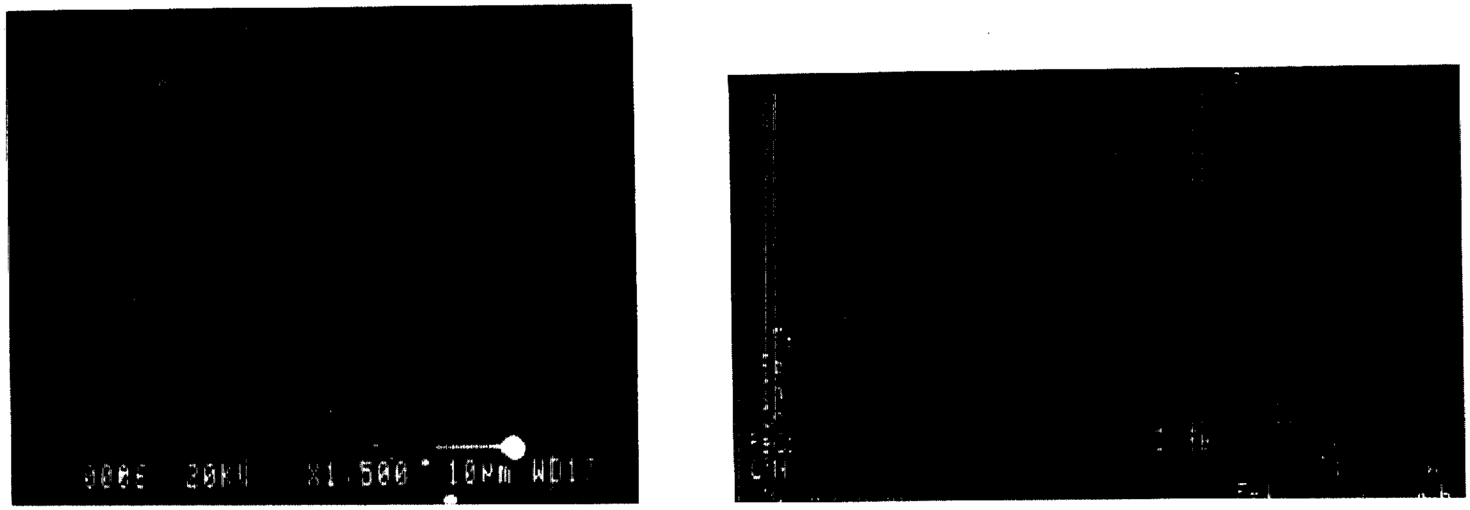
(i) Oxide.



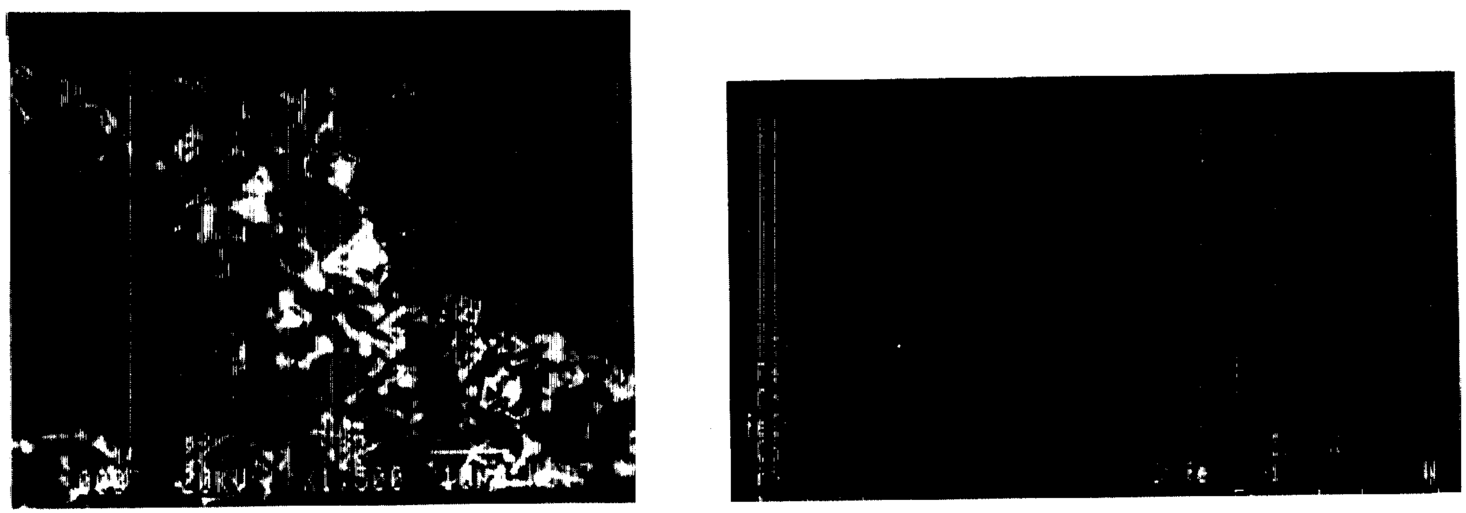
(ii) Melt near bristle attachment.

(c) Sets of element traces.

Figure 22.—Continued.



(iii) Foreign particle.

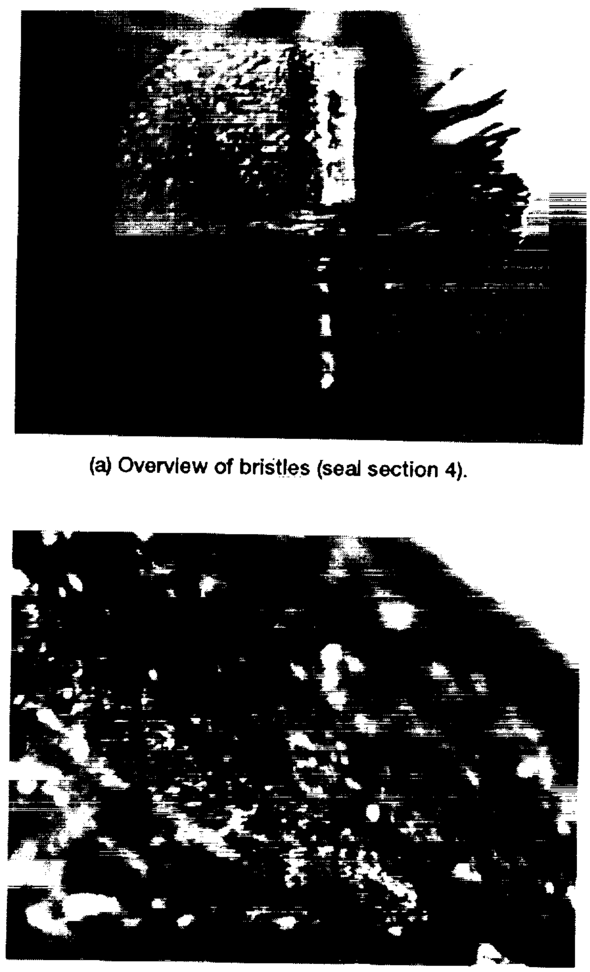


(iv) Resolidification of tungsten.

(c) Concluded.

Figure 22.—Concluded.

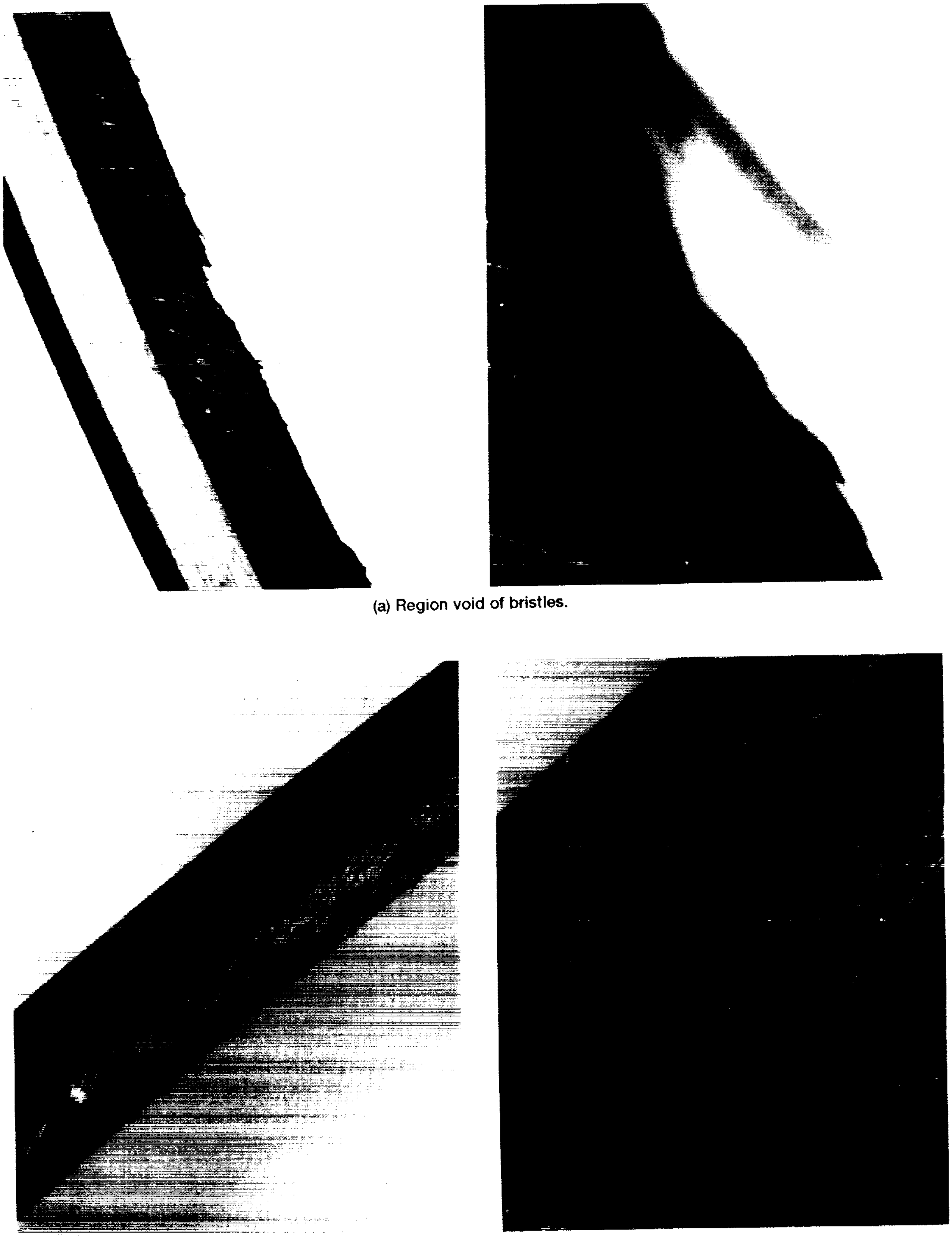
a-5.



(a) Overview of bristles (seal section 4).

(b) Section of brush seal.

Figure 23.—Sets of information for brush segment 4.



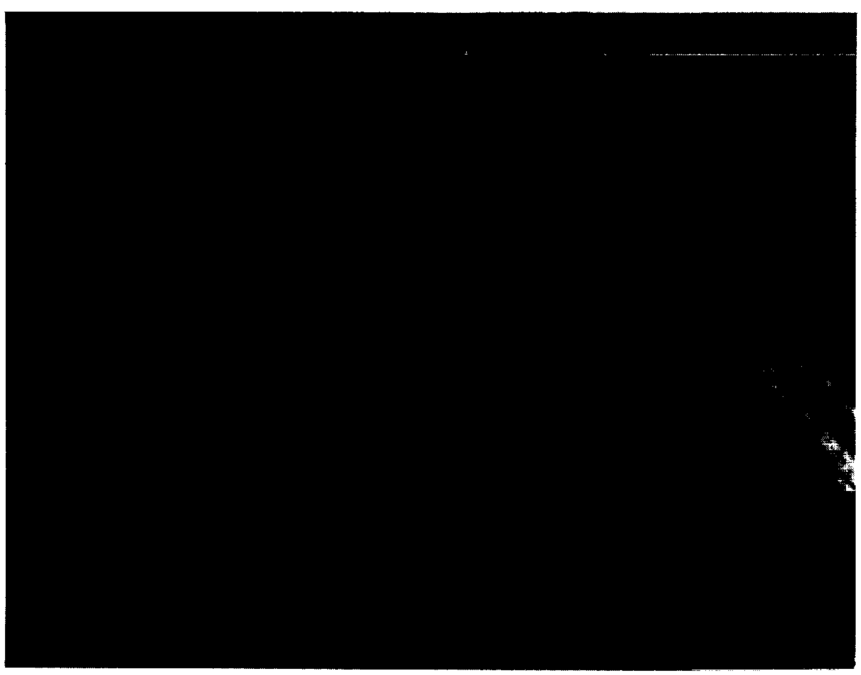
(a) Region void of bristles.

(b) Bent-over bristles (on leading edge but not in core).

(c) Bristles kinked at tips (appear about 2.5 times as long as remaining bristles).

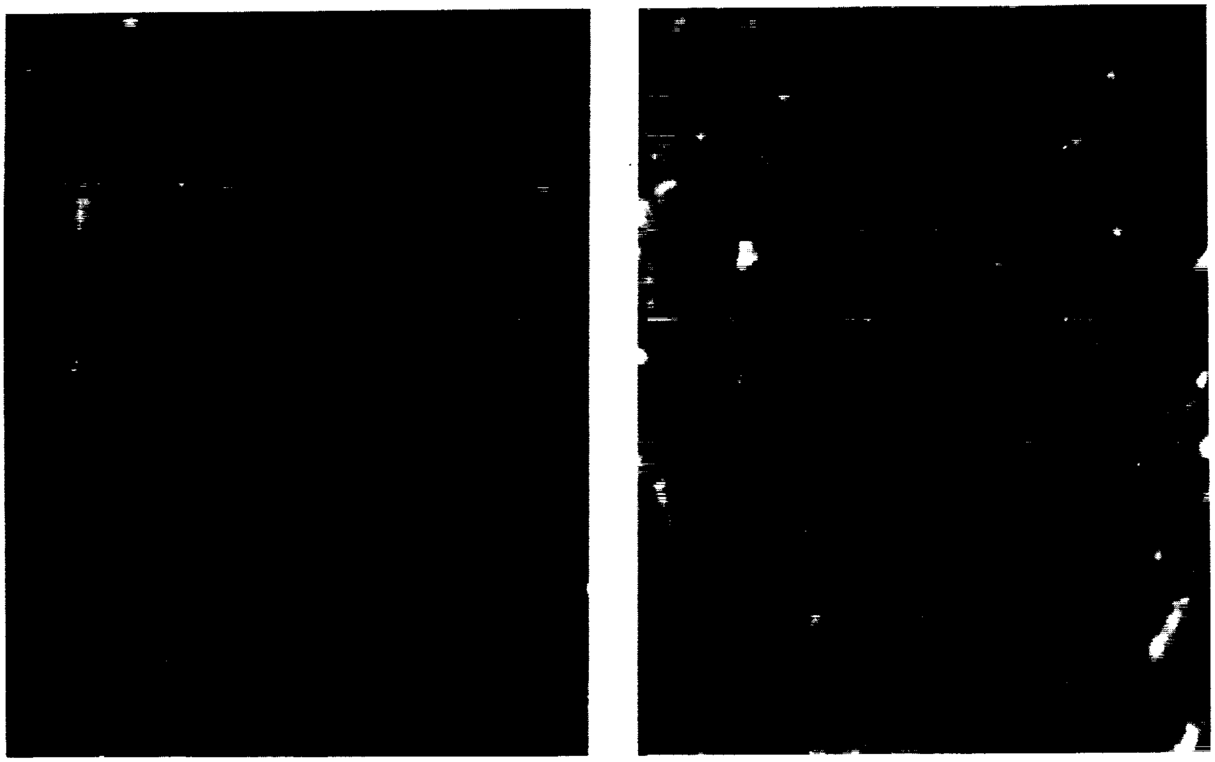
Figure 24.—Geometry associated with installation, noted in post-test evaluation.

(d) Bristles caught within turbine blade gaps.

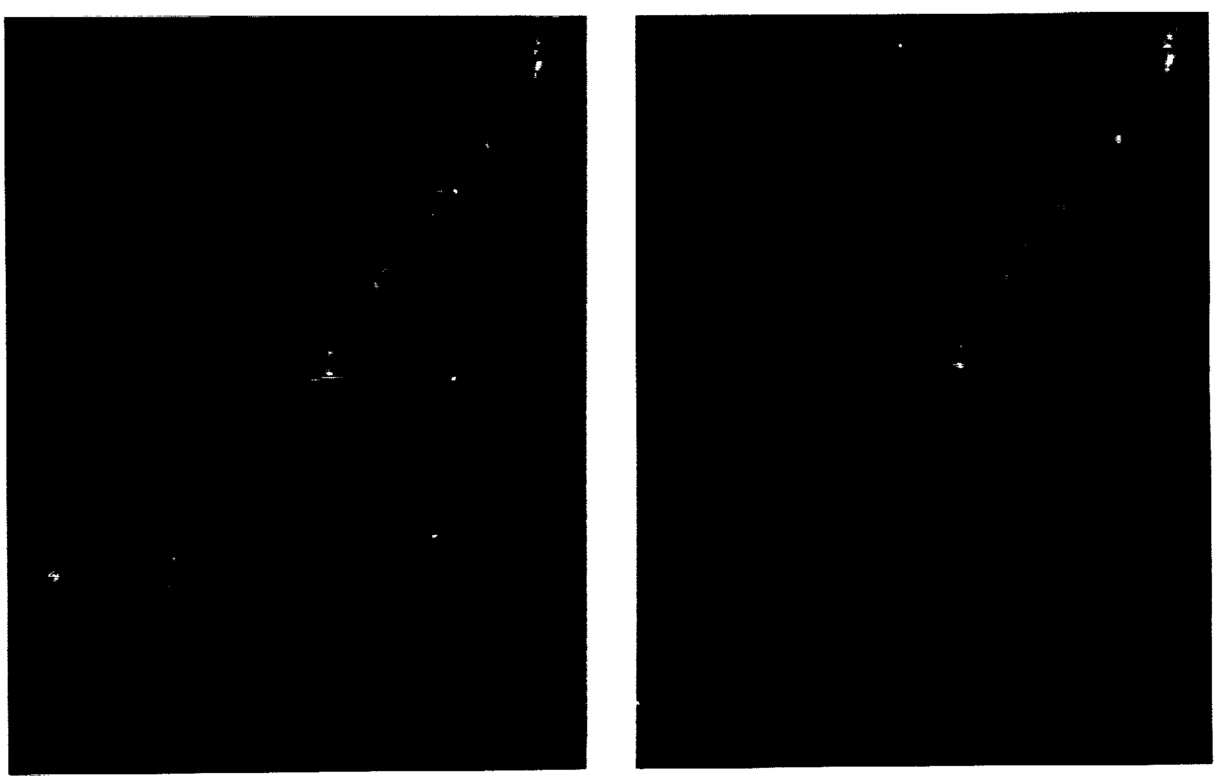


(e) Bristles straight and worn within brush.

Figure 24.—Continued.



(f) "Smearing" of bristle tips.



(g) Oxide scale on bristle.

Figure 24.—Concluded.